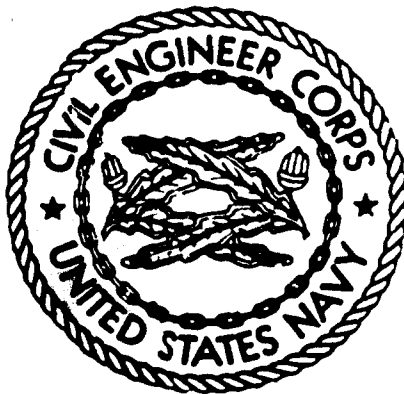


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COMPACTED-SNOW RUNWAYS  
IN ANTARCTICA — DEEP  
FREEZE 61-64 TRIALS

February 1966

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U. S. NAVAL CIVIL ENGINEERING LABORATORY  
PORT HUENEME, CALIFORNIA

# COMPACTED-SNOW RUNWAYS IN ANTARCTICA — DEEP FREEZE 61-64 TRIALS

Technical Report R-399

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by

R. C. Coffin, Jr.

## ABSTRACT

In Deep Freeze 61, NCEL provided technical guidance to a Navy snow-compaction team investigating the practicability of building roads on snow-covered sea ice over McMurdo Sound and runways on the deep snow cover of the Ross Ice Shelf adjacent to McMurdo Station. These investigations and trials continued through Deep Freeze 64. This work was directed toward the development of a layered, compacted-snow runway on deep snow which would support aircraft weighing up to 155,000 pounds with tires on the main wheels inflated to 135 psi; it was only partially successful. During the trials, there were intermittent areas of compacted snow capable of supporting aircraft weighing up to 100,000 pounds with main tires inflated to 90 psi, but low-strength areas prevented takeoffs and landings with aircraft weighing over 25,000 pounds with main tires inflated to 60 psi.

New processing and elevating equipment introduced in the Deep Freeze 64 trials showed considerable promise of producing dense, uniform, high-strength, elevated areas of compacted snow. It was concluded that the trials should continue in Deep Freeze 65 to explore the capabilities of this equipment.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

## CONTENTS

page

### PART I. INTRODUCTION

BACKGROUND . . . . .	1
SNOW AS A CONSTRUCTION MATERIAL . . . . .	1
PRELIMINARY STUDIES IN DEEP FREEZE 61 . . . . .	2
Snow Roads on Sea Ice . . . . .	2
Snow Runways on Deep Snow . . . . .	3
Aircraft Tests . . . . .	3
FINDINGS AND CONCLUSIONS . . . . .	5
REQUIREMENTS . . . . .	5

### PART II. DEEP FREEZE 62 TRIALS

TEST PLAN . . . . .	8
Test Site . . . . .	9
Personnel and Equipment . . . . .	9
CONSTRUCTION . . . . .	10
TESTS . . . . .	12
FINDINGS . . . . .	14

### PART III. DEEP FREEZE 63 TRIALS

TEST PLAN . . . . .	15
Test Site . . . . .	15
Personnel and Equipment . . . . .	15
CONSTRUCTION . . . . .	17
Deep Freeze 63 Runway . . . . .	18
Deep Freeze 62 Runway . . . . .	19
Deep Freeze 62 Runway Extension . . . . .	20
TESTS . . . . .	20
Physical Properties . . . . .	22
Aerial Movement of Fill Snow . . . . .	23
Aircraft Tests . . . . .	24
FINDINGS . . . . .	27

#### PART IV. DEEP FREEZE 64 TRIALS

TEST PLAN . . . . .	28
Test Site . . . . .	28
Personnel and Equipment . . . . .	28
CONSTRUCTION . . . . .	30
Test Area 0-70 . . . . .	30
Test Area 70-140 . . . . .	31
TESTS . . . . .	32
Truck Tests . . . . .	32
LC-47 Tests . . . . .	36
LC-130F Tests . . . . .	37
FINDINGS AND CONCLUSIONS . . . . .	40

#### PART V. SUMMARY

FINDINGS . . . . .	41
CONCLUSIONS AND RECOMMENDATIONS . . . . .	42
ACKNOWLEDGMENTS . . . . .	42
REFERENCES . . . . .	43

## PART I. INTRODUCTION

### BACKGROUND

Polar ice caps are perennial snowfields. Most land and sea areas in those regions also have a light to moderate snow cover during the fall, winter, and spring. Techniques and equipment to utilize this snow as a building material for emergency and temporary roads, runways, and skiways can materially improve year-round operations in these regions.

The Navy first investigated the feasibility of producing static- and dynamic-load bearing snow in 1947. Since then, a cold-processing snow-compacting technique has been developed which produces high-strength snow on deep, perennial snowfields capable of supporting wheeled aircraft with tires inflated up to 75 psi and gross weights up to 75,000 pounds. In addition, techniques have been developed for building roads and parking areas on annual and perennial snow and for improving wind-packed snow for ski-equipped aircraft operations. Current investigations are directed toward developing compacted-snow runways on deep snow which will be capable of supporting wheeled aircraft with tires inflated up to 135 psi and gross weights up to 155,000 pounds.

This report covers investigations conducted on the Ross Ice Shelf near McMurdo Station, Antarctica, between October 1960 and February 1964 — Operations Deep Freeze 61 through 64. These trials, conducted during the austral summer of each year, employed naval personnel as the construction force and were under the technical direction of NCEL.

### SNOW AS A CONSTRUCTION MATERIAL

In February 1947, during Operation High Jump,<sup>1</sup> a compressively compacted airstrip was built by naval construction forces on the Ross Ice Shelf, Antarctica, near Little America IV. It was satisfactory for repeated operations of R4D aircraft on skis, but it provided only spotty support in a taxi test with an R4D on wheels at the end of the flying season. Regardless of this failure, which was attributed to non-uniformity of strength and an inadequate depth of compaction, the taxi test was sufficiently encouraging to warrant further investigation of snow as a construction material.

top of the berms. When this occurred, the road was abandoned. Nevertheless, the experiment demonstrated the feasibility of compacting ice-based snow in Antarctica, but that any ground structure must be elevated above the natural snow surface to reduce the accumulation of drift and minimize maintenance.

### Snow Runways on Deep Snow

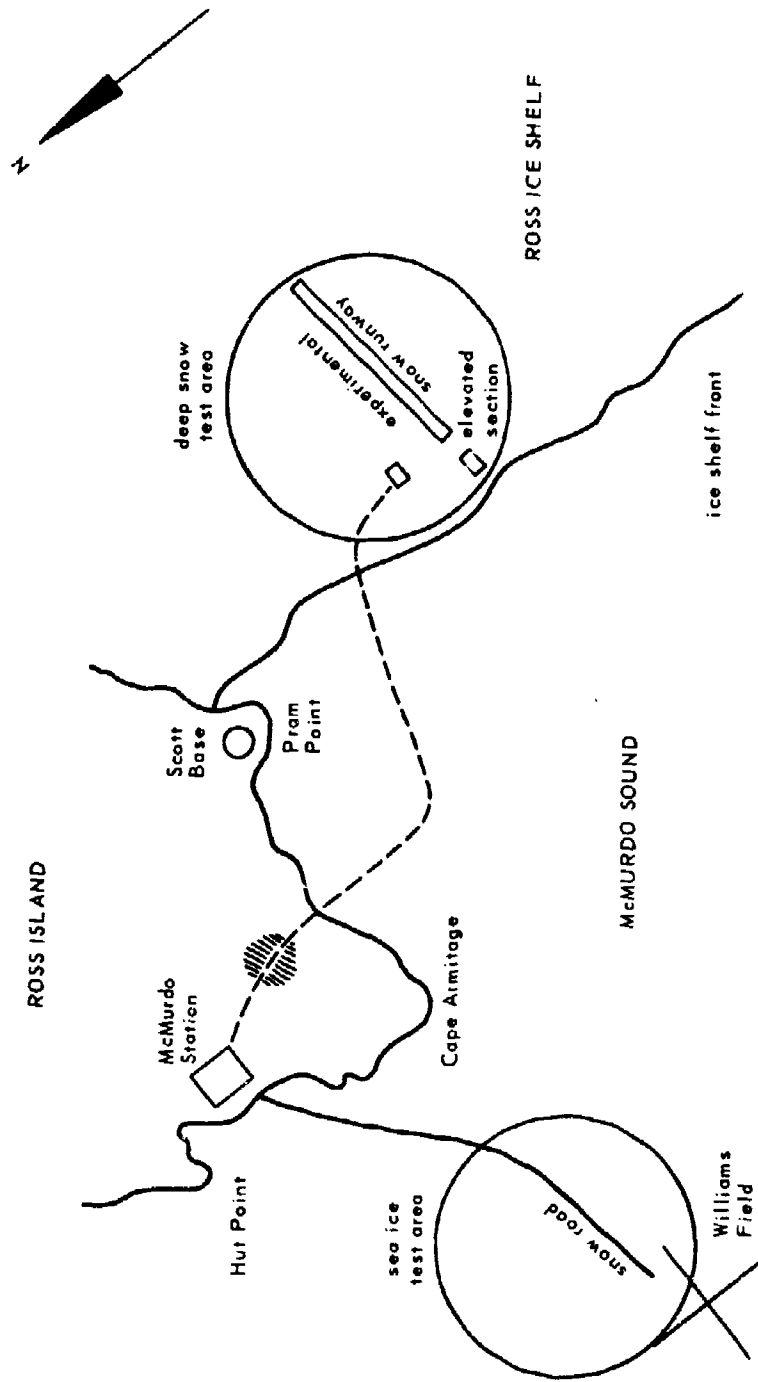
It was initially planned to construct a 7-mile-long compacted-snow road between McMurdo Station and an auxiliary skiway on the Ross Ice Shelf. However, the Commander, Naval Support Forces, Antarctica, requested that a 200-foot-wide by 4,000-foot-long experimental compacted-snow runway be constructed first. Construction started in December; aircraft tests, improvements, and maintenance on the runway continued into early February 1961. A 200- by 400-foot elevated test plot was also constructed in December about 500 feet west of the snow runway (Figure 1). This plot, with a finished grade 3 feet above the natural snow surface, was constructed by dozing and then compacted by depth-processing.

Inspection of the experimental runway in mid-January 1961 showed that the surface was smooth and level. The snow mat was found to vary in thickness from 16 to 28 inches. Further, there was a wide variation in hardness of the mat with numerous areas of very hard snow interspersed with pockets of soft snow. Also, the upper 6 inches of the mat was fairly soft. These conditions were attributed to the use of out-of-date equipment in poor condition; improper preparation of the snow base before depth-processing; omission of the rolling steps during construction; emphasis on production alone rather than production coupled with quality control; excessive digging with rotors during depth-processing; and excessive planing after construction to smooth and level the undulating surface that resulted from poor base construction.

Following inspection, steps were taken to improve the runway by repeated rolling, first with the snow roller and then with the pneumatic-tire roller weighted to a gross load of 9 tons. To obtain a smooth, level surface, multiple passes were made with the finishing drag. This effort resulted in an extremely hard surface and a general increase in hardness through the snow mat. Even so, there were still numerous soft spots in the runway, 1 to 2 feet wide and 5 to 6 feet long, which were attributed primarily to equipment misses during processing.

### Aircraft Tests

The experimental runway was tested three times with aircraft, twice before the extra surface-hardening treatment and once afterwards. The first tests were made with an LC-47 and an LC-130F. These tests showed that the runway was adequately hard and level for repeated takeoffs and landings by an LC-47 on wheels but not an LC-130F. In a taxi test with the LC-130F, tire penetration was excessive and the soft spots permitted wheel breakthroughs in the compacted-snow mat.



Scale: 1 in. = 0.8 mi

Figure 1. Location of DF-61 compacted-snow test areas.

After the extra surface treatment, the runway was tested with a P2V (Figure 2). These tests showed that tire penetration was negligible, but the soft spots still permitted wheel breakthroughs in the compacted-snow mat. While a takeoff test with wheels was impossible, a takeoff with skis was made without extra power in 3,200 feet, or in about the same distance as required on a paved runway with wheels. It was also observed that the propeller blast from the multiengine aircraft caused minor spalling of the very hard snow surface during takeoff.

In early February 1961, a 3-day windstorm deposited about 10 inches of drift over the 4,000-foot test runway. No snow was deposited on the elevated section.

## FINDINGS AND CONCLUSIONS

1. Compacted-snow areas could be built on snow-covered sea ice in Antarctica using the Navy's cold-processing technique.
2. The processed area should be level with or elevated above the natural snow surface to minimize the accumulation of drift.
3. Successful application of the Navy snow-compaction technique to produce uniformly high-strength snow required adherence to the proven processing steps and continuous inspection of the area during construction to insure quality control.

## REQUIREMENTS

Continuation of the compacted-snow-runway studies became of prime concern to the Commander, Naval Support Forces, Antarctica, because during the annual resupplying of the U. S. stations in Antarctica, logistic support of the inland stations is principally by air. The terminal for all continental air operations is McMurdo Station, a coastal installation on the Ross Sea 2,400 miles from New Zealand, where the runways are prepared on sea ice. Each year, several hundred thousand cubic yards of snow which has drifted in during the winter must be removed from the runways before the start of air operations. Then, in the relatively warm months of December and January, the runways are frequently closed because of hazardous surface conditions resulting from rapid, differential deterioration of the ice. Occasionally, during the late season sea-ice breakup, the runway might be lost or might seriously jeopardize air operations.

In early 1961, NCEL undertook a study to determine the feasibility of developing an airport complex on deep snow. The study was originated because of the need for a permanent year-round air facility at McMurdo Station. At that time, the station was serviced with runways on 30- to 40-foot-thick old sea ice. Aside from the annual ice and the thick, older sea ice, which had been used since 1955 to receive all flights into Antarctica, the only fairly stable, open area suitable for an airport complex at McMurdo was the Ross Ice Shelf.



Figure 2. A P2V aircraft taxiing on wheels on the DF-61 compacted-snow runway.

The study, which was directed specifically toward application in the McMurdo area, undertook to identify and solve the problems of constructing, maintaining, and operating a year-round airport on deep snow. It included the use of compacted snow for runways, taxiways, parking aprons, warmup pads, and roads; the location and orientation of administrative, control, maintenance, and fuel- and cargo-storage facilities in relation to each other and to the runway system for drift control; the effectiveness and freedom from drifting of elevated surfaces on deep snow; the development of safe, positive identification systems for snow runways and roads; and the development of a transition ramp between land and deep snow.

Snow-compaction trials, conducted on the Ross Ice Shelf during the summer of Deep Freeze 62 (DF-62), resulted in a compacted skiway which was used extensively for full-load LC-130F takeoffs following breaking up of the annual ice on McMurdo Sound in early February 1962.

In view of this achievement, the Commander, Naval Support Forces, Antarctica, recommended to the Commander in Chief, U. S. Atlantic Fleet, that an operational requirement be established for the development of engineering techniques for the construction of compacted-snow runways capable of accepting wheeled aircraft with gross weights up to 155,000 pounds. The Chief of Naval Operations established the operational requirement and directed increased support of the developmental effort to insure optimum annual progress. This directive implied that compacted-snow runways for wheeled aircraft were also needed at Byrd and South Pole Stations. This new concept dictated a broadening of investigations to include consideration of snow compactability at inland stations as well as at the coastal location of McMurdo Station.

To achieve the objectives of the operational requirement within a reasonable period of time, NCEL envisioned a year-round field effort between October 1962 and February 1965. Based on this premise, a task schedule and cost estimates were prepared around a continuing military-civilian field team operating during that period. However, the Chief of Naval Operations, in approving the NCEL plan, specified that the construction was to be accomplished by military personnel deployed to the area during the austral summer.

## PART II. DEEP FREEZE 62 TRIALS

### TEST PLAN

The preliminary studies, conducted during DF-61, demonstrated that the use of the Navy cold-processing snow-compaction technique to construct a snow runway in Antarctica merited continued investigation. Experience with the snow road over sea ice and the experimental runway on the Ross Ice Shelf evidenced the following:

1. The snow must be properly prepared prior to depth-processing.
2. Quality control must be emphasized.
3. The finished surface must be elevated above the natural surface.

Following the DF-61 experiments, the Laboratory developed a concept of layers<sup>5</sup> for building a compacted-snow runway on the Ross Ice Shelf. In essence, it envisioned construction of successive layers of compacted snow until the runway was elevated 2 feet above the natural surface (Figure 3). The expectation of a successful year-round runway at McMurdo Station based on this concept was predicated on the following:

1. Increased bearing strength with depth of compacted snow.
2. Reduction of the effects of low-strength areas.
3. Minimum drifting on flat elevated surfaces in a snowfield during a single season.
4. High-strength surfaces for traffic on compacted snow with special finishing equipment and addition of free water.

No foreign materials were to be used in this construction for mass strength, insulation, or hard surfacing. The concept did recognize a need for periodically adding new layers of compacted snow in order to maintain a drift-free, elevated runway.

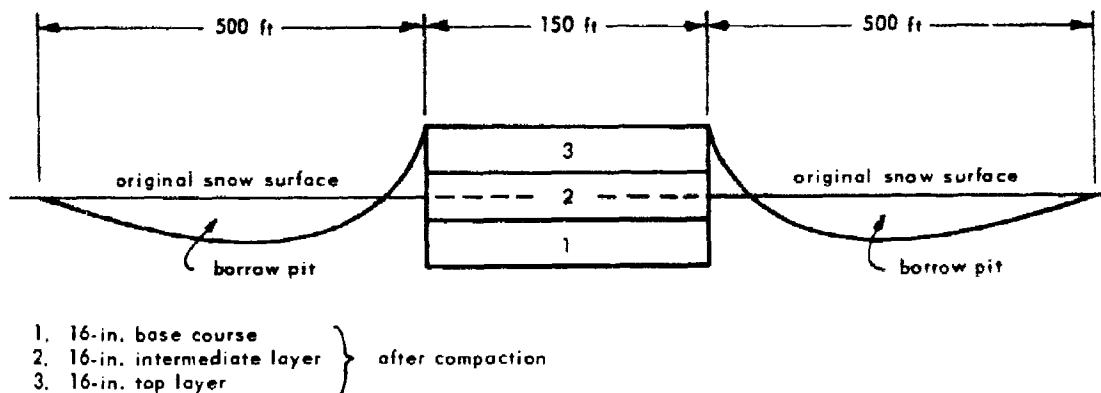


Figure 3. Layered concept of snow compaction.

## Test Site

The initial effort of the DF-62 study was the construction of an experimental elevated runway, 150 feet wide by 5,000 feet long, using the layered-compaction technique. The runway was to overlay the DF-61 test strip on the Ross Ice Shelf and consist of a base course (constructed in DF-61), an intermediate layer, and a top layer or wearing course (Figure 3).

## Personnel and Equipment

The Commander, Naval Support Forces, Antarctica, agreed to provide logistical support for the investigations, including the construction personnel and equipment, which were to be available about mid-October 1961. However, because of unforeseen delays, the Antarctic Support Activities were unable to assign support personnel and equipment for construction of the runway until the end of November.

At that time, five enlisted men with construction rates were assigned to the field work. Four of the five men had had two seasons' experience with snow compaction at Squaw Valley, California,<sup>5</sup> and another season in the Antarctic during DF-61.<sup>4</sup> The fifth man had had no previous experience with snow compaction; however, he had participated in DF-61 as a member of the summer support forces of ASA.

NCEL assigned engineers and technicians to the field team and was responsible for technical guidance of the construction and for conducting the physical testing of the experimental work.

The snow-compaction and tractive equipment assigned by ASA for the construction work was outmoded and in poor mechanical condition. Much of it had been used for three seasons in Squaw Valley, California; the remainder had been shipped to Antarctica in 1955 for Deep Freeze I operations.

## CONSTRUCTION

Field work started in late October 1961 with an examination of the DF-61 areas (Figure 4). About 27 inches of wind-blown snow had accumulated on the runway during the winter. The average hardness of the 20-inch-thick buried mat was about 850R. The elevated section was easily defined; however, an average of 4 inches of snow had drifted across its surface, which was attributed principally to the existence of a low berm along the south side of the plot. The average hardness of the elevated section was also about 850R.

The centerline of the DF-61 runway was staked, and the boundaries of the DF-62 plot were established. Three lines of bamboo marker poles (Figure 4) were placed at right angles to the centerline of the test areas to facilitate measurement of drift during the season. One line was located at the center of the DF-61 elevated section; the other two were at 1,000 feet and 3,000 feet from the west end of the runway. The lines extended 2 miles to the south and 1 mile to the north of the runway.

The assignment of three construction personnel in mid-November made it possible to initiate repair of the construction equipment. Almost 2 weeks were required to make two snow tractors,<sup>7,8</sup> two snow mixers,<sup>9</sup> a snow roller,<sup>10</sup> and two snow drags<sup>11</sup> operable and to assemble two snowplanes.<sup>12</sup>

Processing of the 150-foot-wide, 5,000-foot-long intermediate layer was started late in November. The centerline and west end of this layer coincided with the centerline and west end of the DF-61 runway; however, the east end was 1,000 feet beyond the east end of the base course. This extended area was to be used for special surface-hardening tests.

The intermediate layer, constructed from the snow covering the DF-61 mat, was treated by precompaction, depth-processing, and double depth-processing techniques.<sup>5</sup> Compressive compaction and leveling of this layer reduced its depth from 27 inches to about 22 inches. Using the 3-pass mixing technique and a cutting depth of 24 inches, depth-processing was designed to integrate the overburden into the top of the DF-61 mat. However, the surface of the year-old mat could not be penetrated by the outmoded, slow-speed rotors of the snow mixers. Consequently, the new course was not interwoven with the DF-61 mat; furthermore, processing of the full 22-inch depth of the layer was complicated by the tendency of the rotors to bounce off the hard, slab-like underlying mat. This bounding motion required the equipment operators to maintain continuous, close control of the rotors to insure total mixing.

Construction of the 150-foot-wide by 4,000-foot-long top layer was started in late December. The snow used to construct this layer was obtained from borrow areas which paralleled the runway (Figure 3). Using the Model 40 snowplane as a grader, the snow was moved laterally across the surface to the experimental layered runway (Figure 5). This proved to be an extremely time-consuming effort. To minimize the depth of excavation in the borrow areas, much of the 45,000 cubic yards of fill was moved 300 feet or more. This procedure prevented the formation of mammoth snow traps adjacent to the runway, but it necessitated rehandling of the snow. The layer was processed by the same techniques used for the base course.

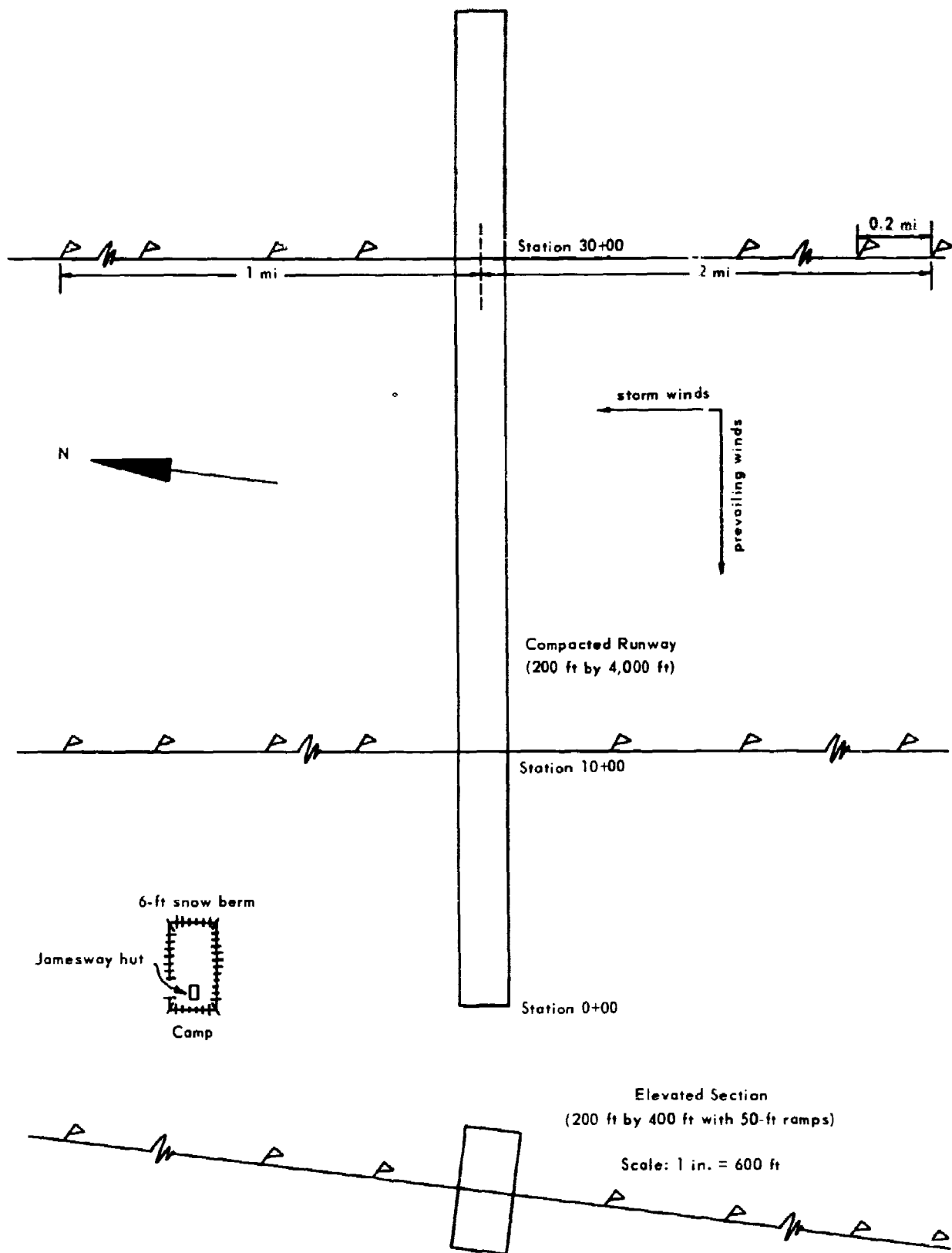


Figure 4. DF-61 test area, with DF-62 drift lines.

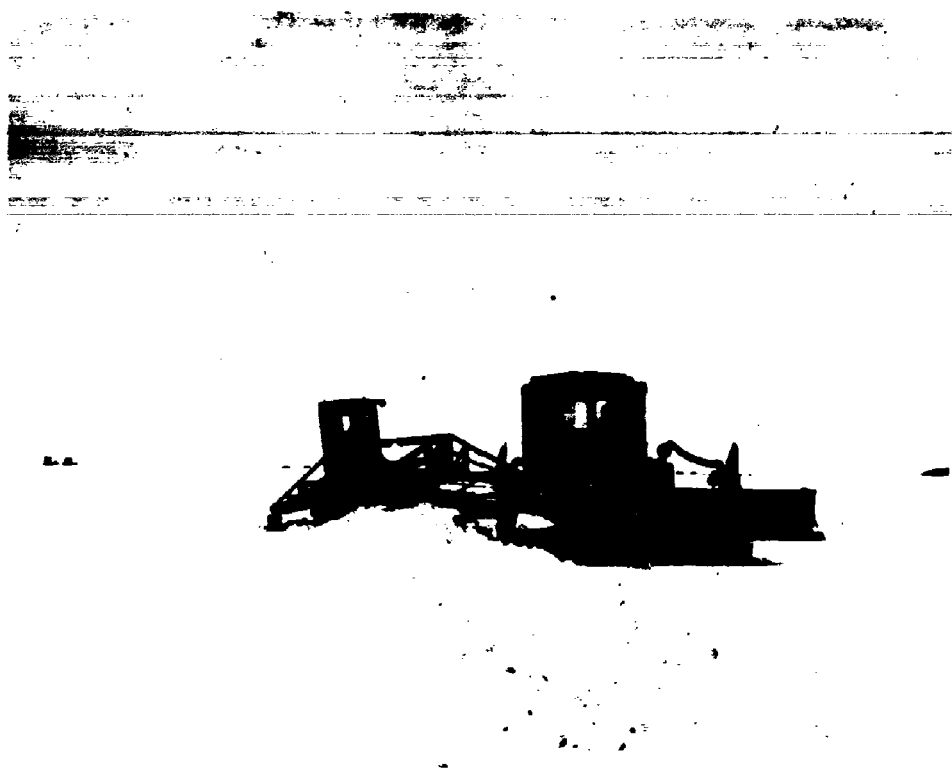


Figure 5. Grading snow for second layer of DF-62 compacted-snow runway.

Frequent mechanical failures in the construction equipment prolonged the processing time. Further, the construction was accomplished during the summer season rather than during the cooler spring season as originally planned. Consequently, an extended period of elevated air temperatures in December 1961 and January 1962 retarded the development of high early strength in the mat and prevented wheeled-aircraft taxi tests on the runway.

## TESTS

Unseasonably warm weather during January, coupled with continuing equipment problems, prevented completion of all the scheduled work. The special surface-hardening tests on the extended area (Figure 6) were omitted. Furthermore, because of the ice breakup on McMurdo Sound in late January and early February 1962, the NCEL test team had to leave before the compacted-snow runway had sufficiently age-hardened under favorable cold temperatures to test it with wheeled aircraft.

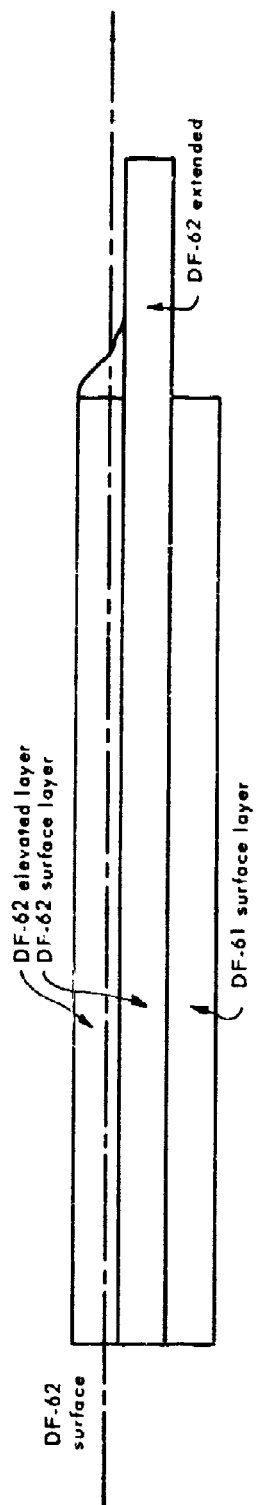
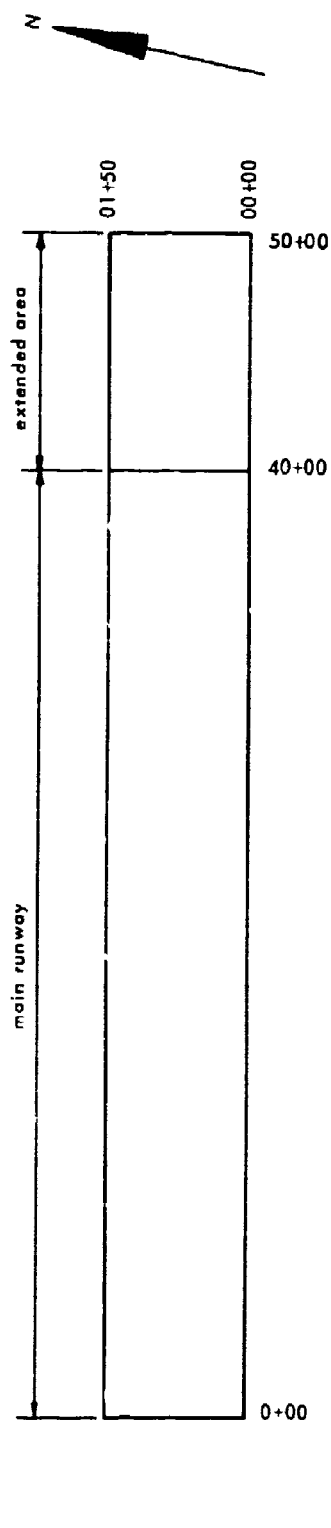


Figure 6. DF-62 compacted-snow runway and extended area.

Breakup of the bay ice also forced air operations at McMurdo to move from the sea-ice runways to an unprepared skiway on the Ross Ice Shelf adjacent to the NCEL processed runway. This change increased the takeoff run for LC-130F cargo aircraft from 3,000 feet on wheels to 7,000 feet. It also reduced the cargo payload from 10 tons to 7 tons.

An experimental takeoff on skis from the NCEL compacted-snow runway showed that an LC-130F with a 10-ton payload could take off without jet assist in 3,000 feet, or the same distance as on sea ice. This was a 50% reduction in takeoff distance with nearly 50% greater cargo loads than were possible on the unimproved skiways. Consequently, the compacted-snow runway was used for 30 full-load ski takeoffs during February 1962. Thus, 117 tons more cargo were moved with 17 less flights during the month using the NCEL runway, which resulted in a savings of at least \$150,000.

Ski operations from the compacted-snow runway were so encouraging that the operating forces took steps to improve the takeoff characteristics of the unprepared skiway. It was leveled with the snowplane and the surface smoothed off with the snow-leveling drag. By mid-February, this work, coupled with increasingly colder weather and the compacting action of taxiing ski aircraft, resulted in a skiway suitable for an LC-130F takeoff on skis in 4,000 feet with a 10-ton payload. Although the takeoff run was one-fourth longer than that required on compacted snow, the results were most gratifying. While the technique used at McMurdo employed aircraft skis for compressively compacting the snow instead of a snow-compacting roller,<sup>5</sup> it was demonstrated that good skiways can be constructed in a polar region.

The stability of the surface of the compacted-snow runway during the period of repeated use was very impressive. The only surface changes observed were a slight indentation (less than 1/2 inch) of ski tracks down the center of runway and the development of a progressively harder surface. Spalling from propeller blast was insignificant, and except for small finger drifts along the storm-wind edge of the runway, the elevated surface was clear of drift and in excellent condition at the end of February.

## FINDINGS

1. The Navy snow-compaction techniques and equipment available in DF-62 were satisfactory for building and maintaining aircraft skiways and limited-use runways; but further improvement was needed for successful application in a compacted-snow-runway complex capable of continually handling heavy cargo aircraft on wheels.
2. Successful employment of the techniques and equipment necessitated adjustment to local conditions, continuous quality control to insure uniformity of compaction, and construction in below-freezing temperatures for hardness growth.
3. To expedite construction of additional lifts using the layered concept, a method was needed for rapidly transporting snow from the borrow area to the runway.

### PART III. DEEP FREEZE 63 TRIALS

#### TEST PLAN

Breakup of the ice on McMurdo Sound in February 1962 not only forced the NCEL test team home, but it was also responsible for the snow-compaction construction camp going to sea. However, the compacted-snow runway was not affected by the breakup; on the contrary, its utilization for the takeoff of ski-equipped LC-130F aircraft contributed materially to the antarctic air operations. The ability of the partially completed layered runway to withstand repeated use resulted in the establishment of an operational requirement for compacted-snow runways in Antarctica.

#### Test Site

Although the ice breakup in January and February 1962 did not directly affect the DF-62 test area, there were indications that the area could be affected in future years. In planning the DF-63 field work, it was decided to abandon the former site and relocate further to the east on the Ross Ice Shelf. A new 150-foot-wide by 7,000-foot-long runway complex was located 2,000 feet east of and in alignment with the DF-62 runway (Figure 7). A new 18-man construction camp was to be sited about halfway between and 1,000 feet north of the two runway sites.

#### Personnel and Equipment

A 6-man NCEL technical team was deployed to McMurdo Station between 11 and 28 October 1962. Initially, military support personnel were not assigned full time, but were made available in limited numbers on a day-to-day basis when not required for other more urgent work. The full 11-man MCB-8 military construction force was not available until early December. However, considering the operational conditions that prevailed at McMurdo from mid-October to early December, it would have been difficult to profitably employ all men had they been available from the start of the field effort.

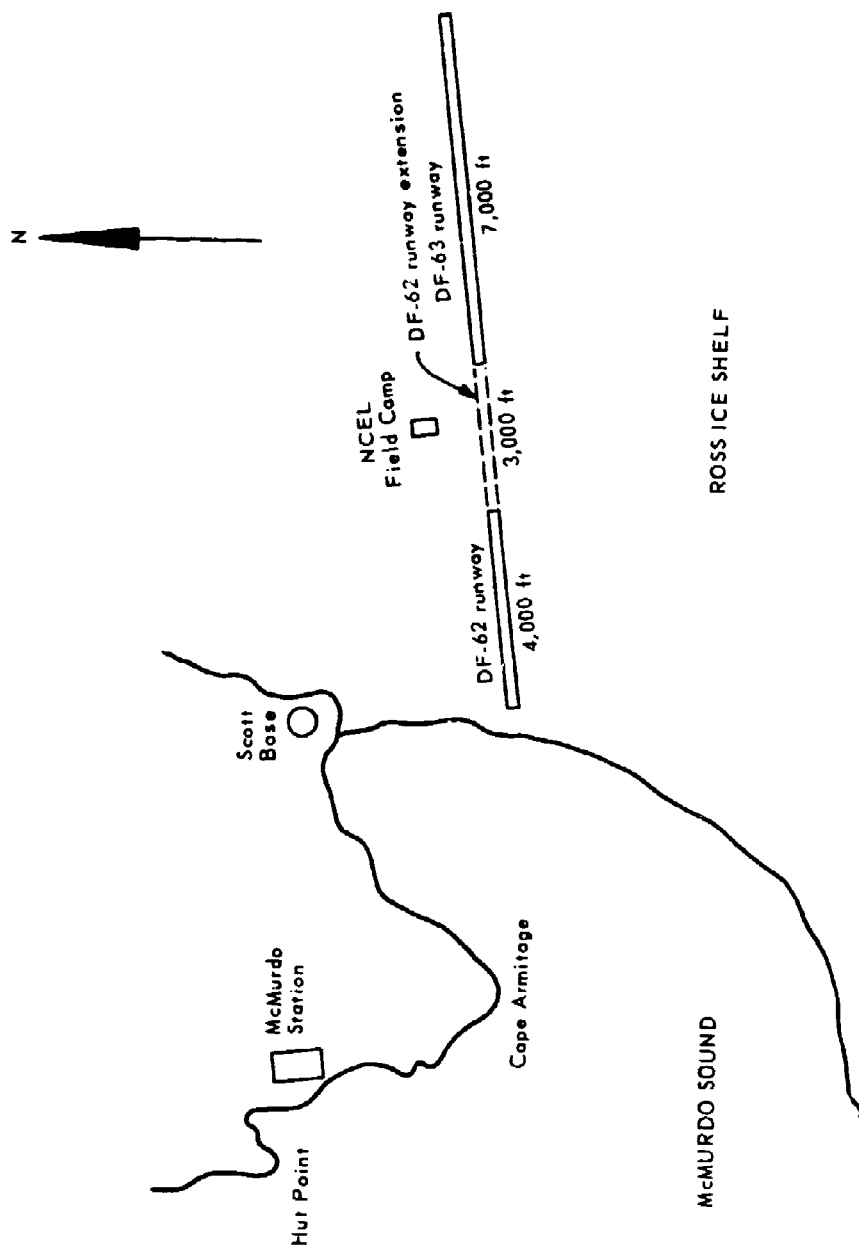


Figure 7. General location of DF-63 snow-compaction effort at McMurdo Station, Antarctica.

The automotive and construction equipment which ASA had agreed to furnish for the construction effort was almost totally inoperative. The few units not deadlined were either in use at the sea-ice runway or else required daily repairs. Restoration of the deadlined equipment was hampered by a lack of parts and the nonavailability of shop facilities. NCEL mechanics were permitted to use ASA shops, tools, and equipment only when they were not being used by the operating forces. Furthermore, a critical shortage and concomitant rationing of fuels drastically curtailed the use of all motorized equipment.

The military personnel made available by MCB-8 were willing and hard workers, but generally they were young, inexperienced men with short periods of obligated service. The equipment operators had had no prior training on snow-compaction equipment and were even unfamiliar with the D2 and D4 snow tractors. Not infrequently, the mechanics had little or no experience with diesel engines.

Gradually, the vintaged tractive and construction equipment was restored to running condition. But without benefit of new parts, the repaired equipment was at best in marginal condition.

Although a camp site had been selected and partially leveled by late October, nonavailability of sleds delayed final preparation of the area and erection of the camp until nearly mid-November.

## CONSTRUCTION

Beginning in mid-October, NCEL technical personnel conducted a detailed examination of the DF-62 compacted-snow test area. The 4,000-foot elevated top layer, which was about 8 inches above the natural surface in February 1962, was very lightly drifted. New snow ranged in depth from 1 to 5-1/2 inches, but averaged less than 3 inches. In dramatic contrast was the drifting on the 1,000-foot extended test layer at the east end of the DF-61 runway (Figure 6). This section, which had been depressed 8 inches below the natural surface, was blanketed with 18 to 30 inches of winter drift.

The runway, constructed in layers,<sup>5</sup> was approximately 52 inches thick. The bottom layer, processed in DF-61, was about 20 inches thick; the intermediate and top layers, both processed in DF-62, were each 16 inches thick. Hardness tests along the centerline of the 4,000-foot strip disclosed the following:

1. In the top 3 to 4 inches of the mat, the hardness varied from 200 to 2,800R, with an average of 1,300R.
2. In the lower 48 inches of the mat, the hardness varied from 400 to 4,050R, with an average of 2,440R.

Following selection and layout of the DF-63 test area, both the DF-62 and DF-63 runways were instrumented with thermocouples. Thereafter, the DF-62 runway was observed periodically for density, hardness, confined shear, and resistance to penetration. The results of these observations are discussed under Tests.

## Deep Freeze 63 Runway

By early December, repairing of equipment had progressed sufficiently that construction could be started on the Deep Freeze 63 Runway. Again, the major construction effort was made during the height of the summer season when prolonged periods of high ambient temperatures combine with intense solar radiation to retard age-hardness growth in the processed snow.

Construction of the first layer of the DF-63 test area was prolonged by snow storms and periods of near-zero visibility. Progress, even during favorable weather, was somewhat less than desired because of inexperienced personnel and the need to work out certain new technical and equipment problems encountered in the use of cross-pattern depth-processing. This new technique was designed to mix the snow better and to minimize processing holidays. The snow mixers proceeded diagonally from one side of the runway to the other in about 3,000 lineal feet. The primary and secondary processing lanes for each layer were diagonally opposite.

By the end of December 1962, only about two-thirds of the primary processing on the first layer had been completed; or, less than 25% of the total construction had been achieved. Accordingly, the following changes were made to the construction plan for the remaining 2 months of the antarctic summer season:

1. Construction of the DF-63 runway would be carried through the double-depth-processing phase and then terminated.
2. To collect snow during the winter for the second layer of the DF-63 runway, 24- to 30-inch-high windrows would be built along the 7,000-foot length of the runway at about 40-foot intervals to trap the snow.
3. The 4,000-foot DF-62 runway would be extended 3,000 feet for use as a test area for moving snow with a tractor-mounted snowplow.<sup>13</sup>
4. Following aircraft and surface-hardening tests of the 4,000-foot section of the DF-62 runway and double-depth-processing of the 3,000-foot extension, the entire 7,000 feet would be built up, if possible, and double-depth-processed.

Primary processing of the first layer of the DF-63 runway continued into January 1963; however, processing time was further prolonged by having only one snow mixer available. This unit, a Model 42 mixer,<sup>9</sup> had to be used for depth-processing of both the DF-63 runway and the extension to the DF-62 runway. By 11 January, primary depth-processing of the DF-63 runway had been completed. At that time, a 2,000-foot, 21-day-old section of the runway was tested for uniformity of depth and hardness. The average depth of the material which had been singly processed was 21 inches, with individual depths ranging from 20 to 24 inches. The average hardness, computed from 15 test stations, was 422R, or about 70% higher than the average hardness attained by primary processing on the Greenland Ice Cap.<sup>5</sup>

In general, except for two soft-surface areas, the compacted snow was far more uniform in hardness than any produced to that time with the Navy cold-processing technique. This was attributed to the full-width rotor of the Model 42 mixer and a higher peripheral speed (5,665 fpm) for the third and final processing pass. The soft spots were attributed to faults in the equipment. The operating forces had used this mixer for ice cutting during the winter of DF-62 and had bent the frame. Also, an undersized, substitute rear ski had been installed. Consequently, it was frequently difficult to obtain a level, even cut across the width of the rotor. The soft spots apparently resulted from the rotor being canted and, thus, only partially effective.

A lack of equipment and time prevented reprocessing of the entire 7,000-foot DF-63 strip, but secondary treatment was applied to a 2,000-foot section at the west end of the area (Figure 8). This section was prepared for load testing with aircraft by being triple-rolled and surface-hardened. The strip was tested on 6 February with an LC-47 aircraft (see Tests). It was then prepared to collect winter drift for use in constructing the second layer early in the DF-64 season; this was accomplished by grading drift snow into four parallel windrows along the 7,000-foot length of the strip. The windrows ranged from 18 to 20 inches high.

#### Deep Freeze 62 Runway

Except for intermittent testing, the DF-62 runway was untouched until late December. By this time, rising ambient temperatures and nearly continuous sunlight caused about a 57% reduction in hardness of the 3-layer, 52-inch-thick mat. Hardness deterioration was most pronounced in the top 6 inches of the compacted snow. In a 2-month period, the hardness in that layer had decreased 76%. The snow cover, which averaged about 4-1/2 inches but ranged from 1-1/2 to 8 inches, appeared to have little effect on the loss in hardness.

Nevertheless, based on current knowledge,<sup>5</sup> the runway at that time should have been adequate for heavy aircraft. Corings through the runway confirmed the firmness of the snow in all three layers. In anticipation of aircraft tests on the strip, the drift snow was planed and compacted. Tests in early January disclosed that the 6-1/2-inch-deep rolled snow had an average hardness of 195R; this was far too deep and too soft to support heavy aircraft.

Surface hardening with the 13-wheel pneumatic-tire roller and the leveling and finishing drags increased the hardness of the snow cover to 428R within 1 week. The hardness in the surface layer of the snow mat just under the snow cover was 850R. Final rolling and leveling of the top course was completed in early February, at which time the average hardness of the runway, including the 6-inch rolled snow cover, was 922R. The runway thickness, including the snow cover, was 63 inches. Without the snow cover, the average hardness was 974R. A summary of test data from October to early February was as follows:

<u>Date</u>	<u>Average Hardness Index (R)</u>	<u>Loss in Hardness (%)</u>
25 Oct 62	2414	—
20 Dec 62	1029	57.4
12 Jan 63	1029	57.4
1 Feb 63	974	59.9

The DF-62 runway was tested on 6 February with a ski-equipped LC-47 aircraft. Ski landings, wheel taxiing, and wheel takeoffs were included in these tests. Examination of the wheel tracks after departure of the aircraft showed little surface damage. Following the LC-47 tests, the surface of the runway was dressed with the snowplane and the leveling drag. On 9 February, a P2V aircraft, weighing about 60,000 pounds, made a ski landing. Then on wheels, it made an 8,000-foot serpentine taxi run over the runway. The rolled snow cover was crushed by the wheels where the depth exceeded 4 inches. But in no case did the wheels sink deep enough for the skis to touch the snow surface. Because of the drag effect of the moderately hard snow cover on the wheels, however, a ski takeoff was made.

#### Deep Freeze 62 Runway Extension

Construction of the extended area served two purposes: (1) to provide a runway of sufficient length for larger and longer-range aircraft; and (2) to provide a test area for aerial movement of snow. The fill material, obtained from 8-foot-wide borrow pits which paralleled the runway extension, was piled about 4 inches deep and then leveled by planing. Observations and physical property tests were conducted in conjunction with this work.

#### TESTS

Double-depth-processing, using a cross-pattern technique, was planned for the extended area. Primary processing was transverse to the runway, so that secondary processing could parallel the runway. Even using the equipment in an elliptical pattern, considerable time was lost in the turns. The processing time for 300 feet in one complete equipment pass averaged 3 minutes, and the turning and travel time averaged 4 minutes. In the diagonal-processing pattern used on the DF-63 runway, mixing time for the 2,500-foot runs averaged 28 minutes and the turning time averaged 8 minutes. Much of the turning time was due to the high bearing pressure under the single front ski and the wide fixed rear ski on the snow mixer.

A lack of equipment and time prevented the secondary processing of the extension. In the area where the new layer overlapped the single layer built in DF-62, the singly processed layer had an average of 538R after 13 days of age-hardening. The underlying 1-year-old, 16-inch-thick layer had an average hardness of 815R. Where the singly processed snow lay over unprocessed snow, it attained a hardness of 428R in 11 days.

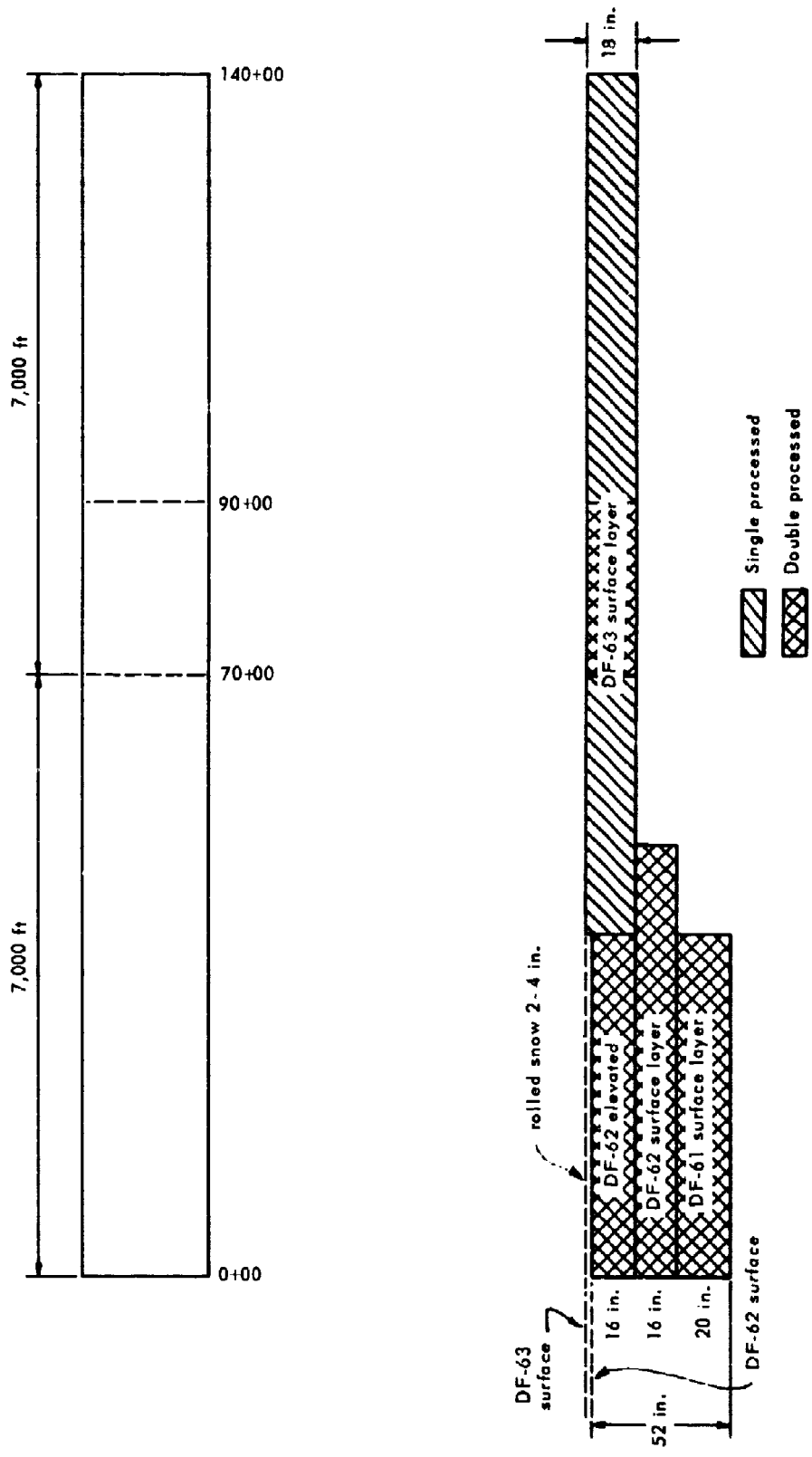


Figure 8. Longitudinal cross-section and plan of the layers processed DF-61 through 63.

The extended area was tested by aircraft at the same time as the DF-62 runway. There were no wheel breakthroughs with the LC-47 aircraft on 6 February; however, considerable plowing of the wheels was observed when the plane encountered the numerous finger drifts that had been deposited during the preceding 24 hours. On 9 February, the 30-ton P2V aircraft did similar plowing in the rolled snow cover where the wheels sheared the surface. In no case did the wheels sink deep enough for the skis to touch the snow.

Following the aircraft tests, two parallel windrows, 145 feet apart and 18 to 20 inches high, were constructed along the edge of the runway to collect fill snow for the DF-64 effort. This trap system, which differed from that used on the DF-63 runway, was dictated by the need for an unobstructed runway for possible additional P2V tests. The two systems would also provide comparative accumulation data.

### Physical Properties

To obtain information for developing better test procedures and improving design criteria for compacted-snow areas, the NCEL technical personnel conducted physical property tests<sup>14</sup> to determine the hardness, density, temperature, and texture of the processed areas. Since many of the conventional test instruments and methods were cumbersome, somewhat limited in reliability, and frequently not related to other test results, NCEL introduced two new tests to determine shear values of the compacted snow. In one test, cylindrical sections were extracted with the 3-inch-diameter CRREL coring auger and tested in confined shear in a mobile laboratory. In the other test, an NCEL-developed, hydraulically actuated device dynamically determined in-place shear in the processed snow. Comparative tests were conducted using the Rammsonde rod, confined shear devices, and hydraulic probe.

The total pounds of resistance in the confined-shear test of the compacted mat were determined by adding the indicated shear for each inch of depth. The pounds of resistance by the probe were determined by subtracting the pressure required to move the probe in free air at the time of the test from the pressures required to push the probe through the snow, and then converting this value to pounds of resistance per inch of depth. The resistance in the underlying snow was subtracted to obtain the total pounds of resistance to the point of penetration in the compacted snow.

A tentative relationship between the Ramm hardness index and the confined shear was developed as follows:

<u>Ramm Hardness Index (R)</u>	<u>Confined-Shear Values (psi)</u>
400	18
550	29
750	45
950	54
1250	59

Confined-shear tests resulted in a wide range of values for snow of various densities from 0.41 to 0.61 gm/cm<sup>3</sup>. The shear values, which ranged from a minimum of 4 psi for 0.41-density snow to a maximum of 42 psi for 0.57-density snow, indicated that above a density of 0.45 gm/cm<sup>3</sup>, the snow strength was more dependent on temperature than on density.

#### Aerial Movement of Fill Snow

A snowplow was mounted on a standard-gage D8 tractor<sup>13</sup> for the aerial transport of fill snow (Figure 9). From preliminary tests in the NCEL camp area, the following was concluded:

1. The tractor-mounted plow worked best on a fairly level, relatively hard surface.
2. The plow was most effective in fairly loose snow of uniform density and hardness.
3. The standard-gage D8 tractor needed a fairly firm work surface.



Figure 9. Aerial delivery of fill snow with a tractor-mounted snowplow.

To test the aerial transfer characteristics of the plow, 80-foot-wide by 3,000-foot-long borrow pits were prepared in late December along each side of the 3,000-foot extension to the DF-62 runway. Over a 3-day period, the areas were rolled, planed, and rerolled. The time lapse was partially to encourage age-hardening and partially due to a lack of equipment. Prior to rolling and leveling, the density of the natural snow was  $0.40 \text{ gm/cm}^3$ , and the hardness index in the top 19 inches was 31R. Two days after rolling, the density was  $0.51 \text{ gm/cm}^3$ , for an increase of 25%, and the hardness was 113R, for an increase of nearly 400%.

A 4-inch-deep fill for the runway extension was deposited with 21 blower passes — 10 along the south side with the wind and 11 on the north side into the wind. The casting area using the side chute averaged about 75 feet wide and was slightly crowned at the quarter points across the runway. The density of the cast material was  $0.49 \text{ gm/cm}^3$ , or slightly less than the roller-packed snow in the borrow pits, but nearly 25% more than the natural snow. One day after casting, the average hardness in this material was 80R, or about 26% greater than the natural snow, but 30% less than the roller-packed snow.

Initially, one 3,000-foot pass with the plow and deadheading back to the beginning point required 1 hour. Because the plow cast from only one side, it was deemed advisable to deadhead back rather than cross the finished runway with the D8 tractor. With experience, familiarity, and modification to the snowplow, the time required for each pass was reduced to 30 minutes. Observations showed that the wings on the plow would occasionally dig in as the unit pitched and rolled. When this occurred, the snow would crowd the augers and break the shear pins. Removal of the wings materially reduced this problem, but did not eliminate the pitching and rolling. However, as the operator became more proficient, he was usually able to elevate the plow before the shear pins were broken.

Following these tests, two alternate methods for the aerial transport of fill snow were proposed to overcome the difficulties encountered with the tractor-mounted plow:

1. Mount an auger and blower on the hood of the snow mixer to laterally move the snow, and use the mixer rotor to cut, pulverize, and lift the snow up to the blower.
2. Mount the snowplow on a heavy-duty, ski-mounted frame similar to the snowplane.

Later study indicated that the second method might be superior, because the snow mixers had some inherent shortcomings that could further aggravate the procedure.

### Aircraft Tests

Two aircraft tests were conducted on the compacted-snow runways in early February. First, the entire 14,000-foot system was tested on 6 February with a ski-equipped LC-47, and then the DF-62 runway and its 3,000-foot extension were tested on 9 February with a ski-equipped P2V aircraft.

LC-47 Tests. An LC-47, weighing about 25,000 pounds, with tires on its main wheels inflated to 60 psi and the tire on its tail wheel inflated to 30 psi, landed on skis at Station 20+00, or mid-point on the DF-62 snow runway. It came to a stop at Station 42+00, where the pilot raised the skis and made a serpentine taxi test on wheels to Station 116+00 on the DF-63 runway (Figure 8); he then turned around and taxied back to Station 0+00 at the west end of the DF-62 runway. In all, the test covered over 23,000 feet: 11,000 feet on a single layer of singly processed snow; 4,000 feet on a single layer of double-processed snow; 2,000 feet on a 2-layer runway consisting of a base course of double-processed snow and a top layer of singly processed snow; and 6,000 feet on a 3-layer runway consisting of double-processed snow covered with 2 to 10 inches of snow rolled with a pneumatic-tire roller. There were no breakthroughs during this test, but drifting during the previous 24 hours had deposited numerous finger drifts up to 10 inches deep over the entire runway. Considerable power was required for the wheeled aircraft to plow through the drifts.

Following the long taxi test, the pilot made a wheeled takeoff on the DF-62 runway (Figure 10) and a ski landing. The ski landing was necessary because of the inadequate marking of the runway and the poor visibility and lack of depth perception that existed at the time. After landing, the pilot made a second wheeled takeoff and departed. In each takeoff, the ground roll was very smooth, and the aircraft was airborne in 1,600 feet.

Examination of the wheel tracks after departure of the aircraft showed little surface damage to the DF-62 runway; but in the DF-63 runway, considerable plowing was observed through the finger drifts. Two of the areas were examined in detail; one at Station 6+71 in the top course of the 3-layer mat which had been double-processed (Figure 8), and the other at Station 55+87 in the single layer, singly processed snow where the aircraft turned around. Surface abrasion occurred to depths of 6 inches in the mat where the surface material had a vertical confined shear value of less than 18 psi. Where the vertical shear value was 25 psi or above, the aircraft rolled on the surface. In no instance was the surface abraded below the 6-inch level.

P2V Test. Following the LC-47 tests, the surface of the 4,000-foot DF-62 runway and its 3,000-foot extension was dressed with the snowplane and the leveling drag. The width of the dressed area was 120 feet. This work produced a 12- to 15-inch-high spoil bank of snow along each edge of the dressed area. In addition to the spoil banks, barrels were set 1,000 feet apart along the runway, and a cluster of seven drums was set up on each side of the runway at Station 0+00. Also, a row of seven drums spaced about 100 feet apart was set up on the centerline of the runway between the edge of the ice shelf and Station 0+00.

The P2V, weighing about 60,000 pounds with tires on its main wheels inflated to 90 psi and its nose-wheel tire inflated to 105 psi, landed on skis near Station 5+00 and came to a stop near Station 42+00 (Figure 8). Visibility was excellent; there

were no clouds and no overcast. After stopping, the aircraft turned around on skis and then came up on its wheels for a serpentine taxi test from Station 40+00 to Station 0+00 and return. The 8,000-foot taxi run was made on wheels but the rolled-snow cover was crushed where its depth exceeded 4 inches. In no case did the wheels sink down to the skis, but the rolled snow was sufficiently hard to create a drag on the wheels where they sheared the surface. Consequently, the pilot selected to make a ski takeoff. Starting at Station 0+00 and using the auxiliary jet engines, the aircraft was airborne in 3,200 feet.

At the time of the P2V tests, the hardness index in the 4 to 8 inches of rolled surface snow was 414R. Three days after tests, the rolled snow was examined for hardness, density, and confined shear. During the intervening period, the night temperatures ranged from 2 to 5°F. As a result, the hardness of the rolled snow increased 47% to an average of 609R. Its density was 0.55 gm/cm<sup>3</sup>, or about the same as the singly processed snow, and its vertical confined shear ranged from 15.1 psi at one location to 41.1 psi at another, for an average of 23.9 psi. Based on aircraft tests at Hard Top II, Greenland,<sup>15</sup> this condition was suitable for marginal support of a P2V on wheels.

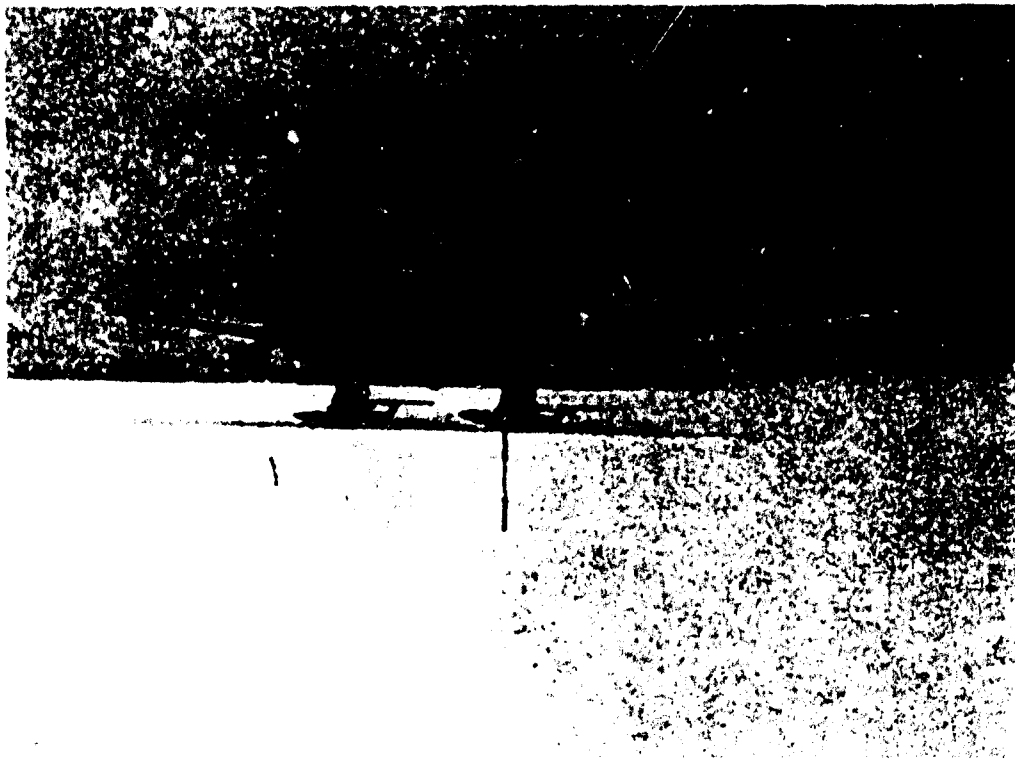


Figure 10. An LC-47 aircraft taking off on wheels on the DF-63 test runway on 6 February 1963.

## FINDINGS

1. Review of the background and performance of the military construction personnel assigned for DF-63 confirmed the need for a nucleus of well-trained enlisted personnel for snow compaction.
2. Redesign of the snow mixer's ski-suspension system was needed to reduce turning and travel time, and redesign of the rotor drive and hood-suspension system was needed for better control of the mixed material and to eliminate undulations in the processed snow.
3. Tests on the aerial transport of fill snow with the tractor-mounted snowplow showed the need for a heavy-duty carrier similar to the ski-mounted frame of the snowplane.
4. The single, 18-inch-thick layer of singly processed snow was adequate to support the 60-psi main-tire load of an LC-47 aircraft, even when built under antarctic summer conditions.
5. The 3-layer, 52-inch-thick, double-processed snow mat was adequate to support the 90-psi main-tire load of a P2V aircraft, but where the rolled-snow cover on this mat exceeded 4 inches in thickness, it sheared under the wheel load.

## PART IV. DEEP FREEZE 64 TRIALS

### TEST PLAN

The DF-63 field effort showed the need for improved equipment and further experimentation with the snow-compaction techniques. Accordingly, field studies were planned for the DF-64 summer season, October 1963 to February 1964.

#### Test Site

The DF-64 studies were to be conducted on the Ross Ice Shelf in the same area used for the DF-63 trials. The extent and depth of drift on the NCEL test area and the condition of the DF-63 compacted-snow runway were to be determined in mid-October. The drift snow over the first 7,000 feet of the runway (Figure 11) was to be compacted in November by double-depth-processing, using the cross-pattern technique. Upon completion of the depth processing, the runway was to be maintained for aircraft testing through February 1964.

If conditions permitted, surface-hardening techniques would be investigated during December and January. Also, beginning in December, drift on the 7,000-foot DF-63 runway was to be compacted. Then in January, it was to be elevated with a 24-inch layer of fill snow. The material was to be aurally transported by improved snowplow carriers. Processing of this layer was to be completed in February.

#### Personnel and Equipment

As in previous years, NCEL provided technical guidance for the DF-64 field effort and conducted all physical testing on the compacted snow. An 8-man team was deployed to Antarctica by 30 October 1963. At that time, Mobile Construction Battalion 8 assigned ten construction personnel and one cook to support the field work. Few of the military had had any cold-weather experience. The two who had been deployed to the Antarctic in DF-63 had but limited experience in operating conventional equipment in the polar climate. Essentially, the construction personnel were totally unfamiliar with the snow-compaction equipment and were poorly oriented in the operation and maintenance of standard equipment under cold-weather conditions. Although willing workers, they were poorly supervised and their energies were frequently misdirected. Their inexperience frequently contributed to equipment breakdowns and further delayed the compaction effort. This again pointed up the need for a nucleus crew of skilled construction personnel trained in snow compaction.

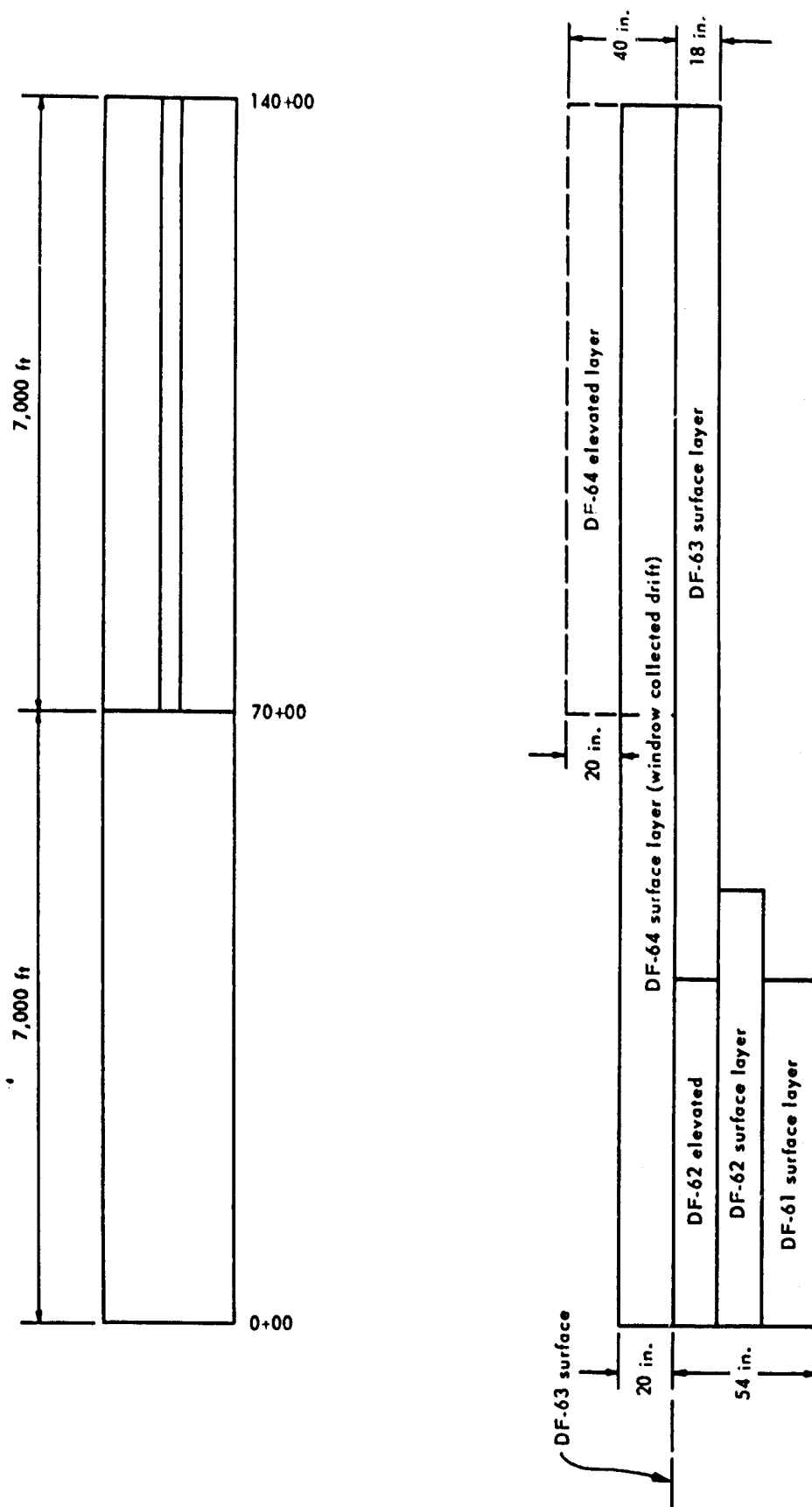


Figure 11. Longitudinal cross-section and plan of the DF-64 test area.

For DF-64 NCEL procured two new D4 snow tractors and two redesigned Model 36/42 snow mixers. Since these units were transported to Antarctica by ship, they did not arrive until late in the construction season. The tractors were received on 24 December 1963, but the snow mixers were not received until 17 January 1964. Therefore, outmoded and unreliable equipment was used for most of the construction season. Further, there was but one old snow mixer capable of depth-processing the drift snow that had accumulated during the winter. This Model 42 unit, used for three seasons at Squaw Valley and three in the Antarctic, was subject to numerous breakdowns during the season. Frequently, the necessary parts were neither available in Antarctica nor could they be made in the ASA shops. Temporary repairs merely extended the unit's useful life from day to day. Although several old Model 24 mixers were available from ASA, their limitations made them totally unreliable for the heavy snow construction required on the Ross Ice Shelf runway.

The new Model 80 snowplane,<sup>12</sup> which arrived at McMurdo too late to be assembled for the DF-63 season, was stored out of doors for the winter. Sometime during the winter, the main girders were run over by heavy equipment and damaged beyond repair. Therefore, an old Model 40 snowplane was again used for leveling and grading. Although the longer span of the Model 80 plane inherently minimizes long-wave surface undulations, a satisfactorily leveled surface may be obtained with the Model 40 plane when it is properly operated.

## CONSTRUCTION

At the end of the DF-63 summer season, the 14,000-foot compacted-snow area had been prepared to trap drifting snow during the winter. To achieve this, windrows of various heights and configurations were constructed along the runway (Part III). Snow accumulated on the test runway in depths varying from 13 to 24 inches, with an average depth of about 19 inches.

### Test Area 0 - 70

In mid-November, the drift snow between Stations 0+00 and 70+00 was rolled and planed, and depth-processing was started. Progress was intermittent, because the snow mixer and prime movers frequently required repairs. Primary depth-processing of the 7,000-foot section required 10 days of around-the-clock operations. After 3 days of age-hardening, the 14-inch-thick compacted layer had an average density of  $0.53 \text{ gm/cm}^3$  and an average confined shear value of 16.4 psi.

Upon completion of these physical tests, secondary processing began. Frequent equipment breakdowns continued to hamper operations, and protracted periods of near whiteout conditions, blizzards, and rising ambient temperatures further impeded progress. At times, visibility was so severely restricted that the mixer operator walked

beside the tractor in an attempt to properly overlap the processing lanes. During blizzard conditions, all work stopped — once, in early December, for about 3 days. Although some drifting was caused by the storm, it was considerably less severe than previously experienced. Generally higher ambient temperatures (Figure 12), which are normal for December, caused a gradual reduction in the strength of the new layer. Unfortunately, much of the secondary depth-processing was accomplished in temperatures well above 20°F. For 10 consecutive days, 21 to 30 December, daily maximum temperatures exceeded 30°F, and 40°F was recorded on 23 and 24 December.

The high temperatures coupled with the solar radiation also adversely affected the mixing and compaction of the snow. The moist snow clogged the mixer hood and formed large balls when it was compacted and screeded by the rear ski of the mixer. The snow also stuck to the surface of the steel roller. Accordingly, mixing was discontinued for several days, and the area was maintained by being rolled during cooler periods of each day. Despite all the adversities, secondary processing of the first 7,000 feet of runway was completed on 29 December. Surface-hardening was delayed for more than a week because of blowing snow and a lack of equipment. Considerable loose snow accumulated on the area; it was removed with the snow-plane. The 13-wheel, pneumatic-tired roller (Figure 13) was used for surface compaction. By mid-January, the 7,000-foot runway was ready for aircraft testing.

Failure to follow proven steps in the construction of compacted-snow areas caused an undulating surface condition to develop late in December. This resulted when finger drifts deposited by winds earlier in the month were not removed from the surface. As the ambient temperatures increased and the strength of the snow decreased, the surface became more washboardy. To correct this condition, the surface was planed and rerolled during the cooler part of the day.

#### Test Area 70 - 140

When the elevated ambient temperatures halted processing on the 0-70 test area, attention was directed toward the 7,000-foot 70-140 test area. In November, snow accumulation over the single-layer test area averaged 19 inches thick. By late December, it had sunk to an average thickness of 14 inches.

Initial rolling of this area was started on 23 December. Because of high temperatures, the rolling resulted in a very irregular surface, with deep troughs and high crests. Extensive leveling and rerolling were required to prepare it for primary depth-processing, which began on 10 January. However, inexperience and inattention to operation of the mixer resulted in an uneven surface. Processing was stopped, the area was planed and rolled, and processing was resumed on 19 January using the Model 36/42 mixers.

A diagonal mixing pattern was also used on this area. However, because of inadequate ski support for the mixers on the freshly processed snow, a skip-lane procedure was used — that is, every other mixer lane in a selected section was

processed the first day and the intermediate lanes were processed the following day. While this resulted in a fairly level finish, it prevented grading and rolling of the freshly processed snow within the prescribed interval.

To reduce the high unit bearing pressure of the mixer skis, the front skis were enlarged, and the rear skis were replaced with a field-fabricated, full-width rear ski. These changes reduced the unit bearing of the skis to about 3 psi.

While the skis were being modified, 10 inches of fill snow was cast on the 70 - 140 runway to bring the total depth of unprocessed snow to 24 inches. The new Model 40, towed snowplow carrier<sup>16</sup> was used to cast the fill snow (Figure 14). Borrow pits for the fill snow were 55 feet wide; they were located along both sides of the test area. With the new carrier, it was found that 1/2 inch of fill could be cast on an 8-foot-wide area at the rate of 167 fpm. This was much faster than any previous technique used for mechanically elevating a compacted-snow area.<sup>13</sup> Using one transporter, 3 days were required to cast a 10-inch layer of fill snow on the 150-foot-wide, 7,000-foot-long area.

After the fill was cast, the area was graded, leveled, and rolled. By this time, the mixer ski modifications were completed, and a strip down the middle of the area was selected for depth-processing, using the mixers in tandem (Figure 15). The lead mixer cut to a depth of 26 inches, and the second unit cut to 24 inches. The first pass was made at a speed of 80 fpm; the second pass, in the same lane, was made at 160 fpm. The total processing time for 4-pass mixing on the 7,000-foot-long lane was 2-1/2 hours. The 4-pass mixing with the Model 36/42 mixers produced compacted snow with a density of 0.60 gm/cm<sup>3</sup> compared with the 0.53 gm/cm<sup>3</sup> compacted snow achieved by double-depth-processing (six passes) with the Model 42 mixer.

As time and weather permitted, three additional lanes were processed before the field season was concluded. Before the field team departed, the area was triple-rolled with the pneumatic-tired compactor. Only during the first pass was there any sinkage in the newly processed snow. During this pass, the surface indentations ranged from 1/2 to 1-1/2 inches in depth.

## TESTS

### Truck Tests

Prior to testing the 0 - 70 runway with aircraft, it was tested with truck traffic in late January. A 6,000-pound power wagon made a longitudinal run from Station 70+00 to Station 9+00 and a serpentine run back to Station 70+00. The truck, equipped with standard tires inflated to 40 psi, operated at speeds from 15 to 25 mph. There was no damage to the surface in this test.

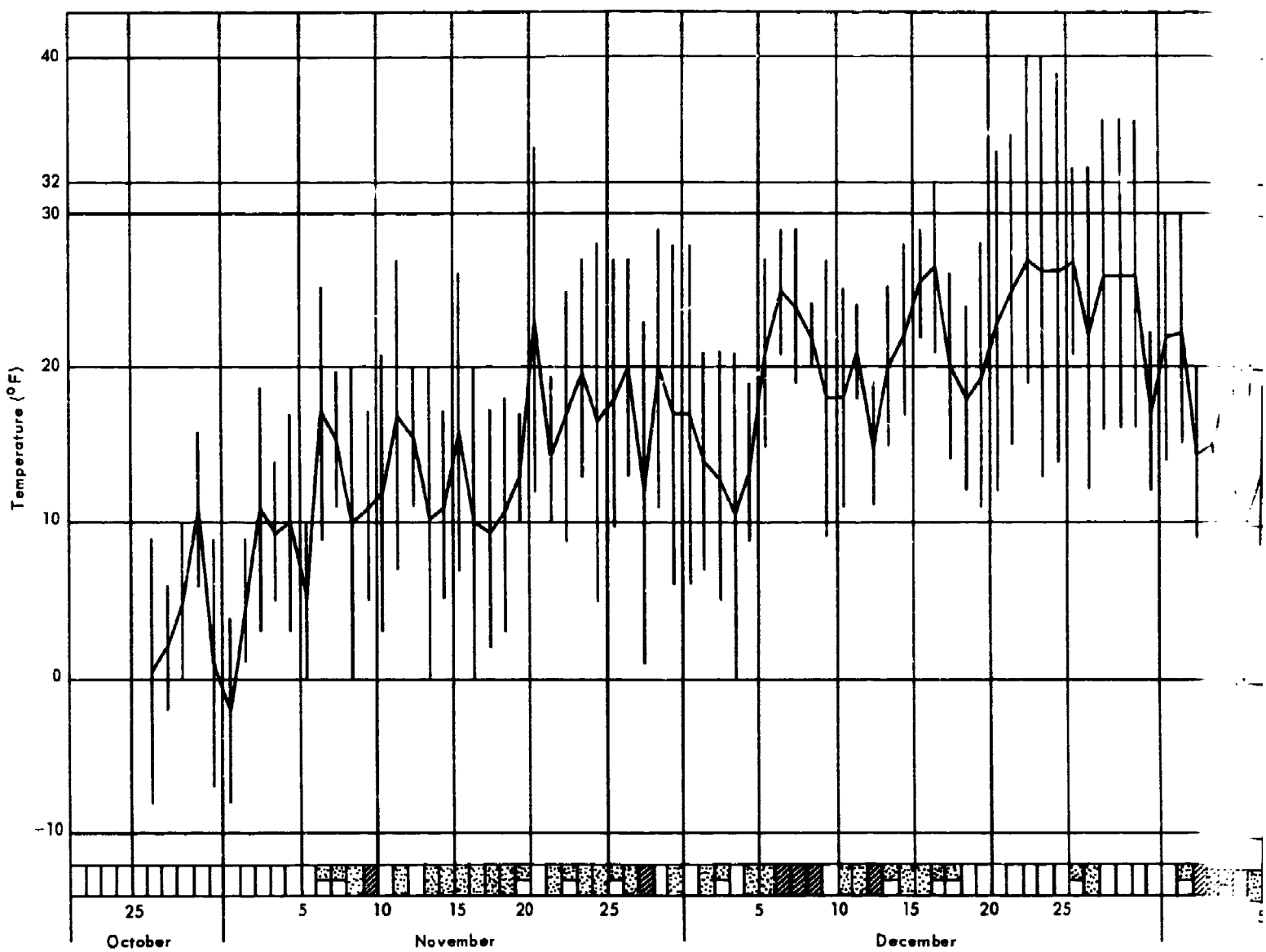


Figure 12. Temperature chart for DF

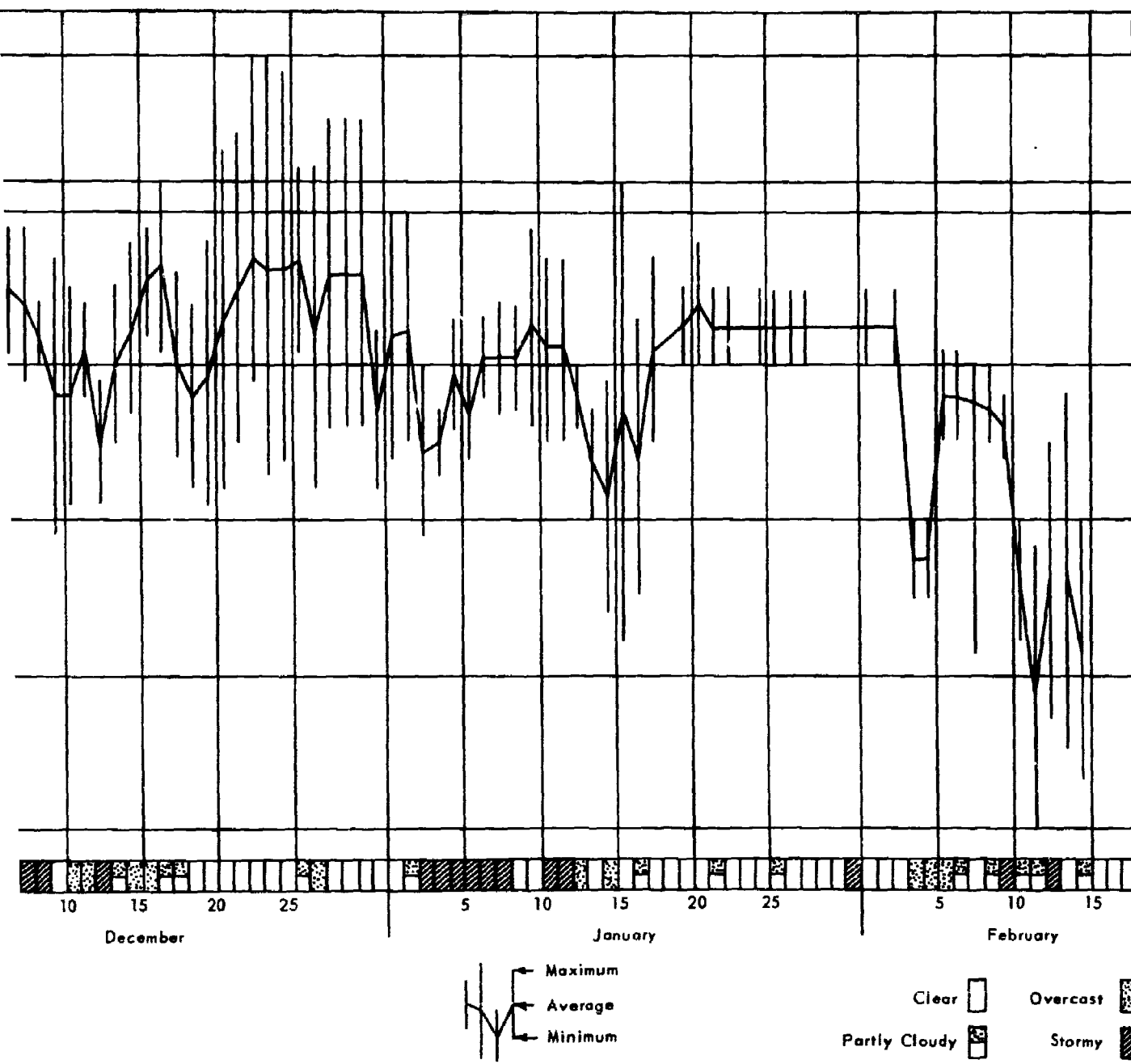


Figure 12. Temperature chart for DF-64.

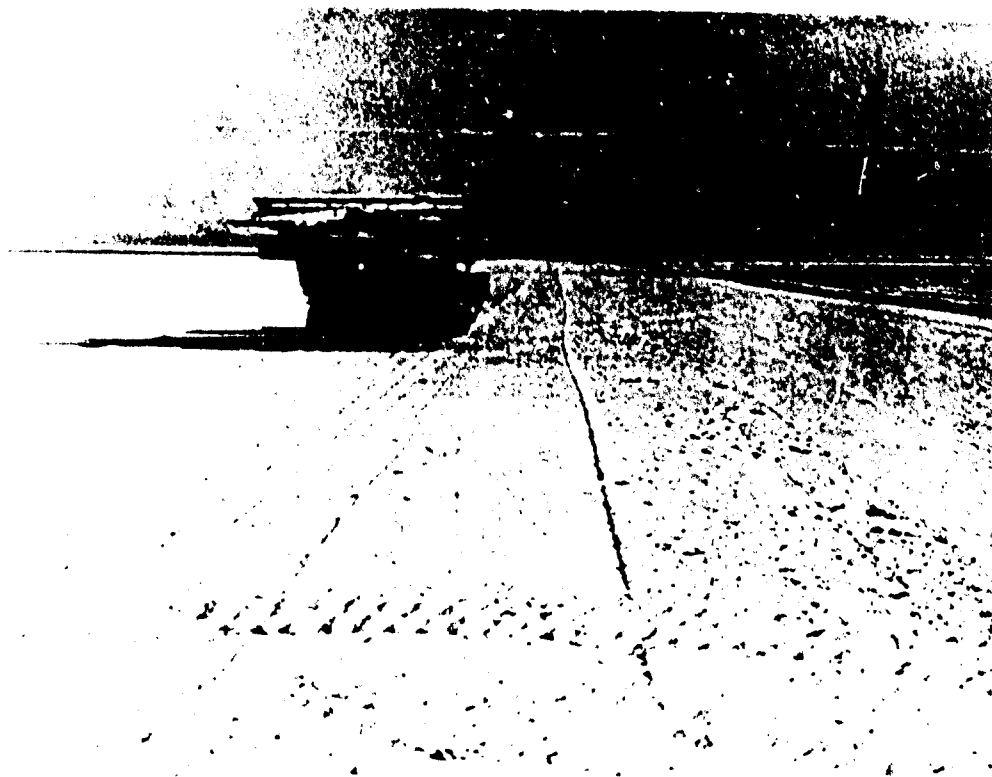


Figure 13. Surface-hardening compacted snow with 13-wheel pneumatic-tired roller.



Figure 14. Casting fill snow on the 70 - 140 test area with the Model 40 snowplow carrier.



Figure 15. Model 36/42 snow mixers processing in tandem on the 70 - 140 test area.

Following this, a 10-ton 6 x 6 cargo truck with standard tires was used to traffic the area. The first test with this truck, made at an empty weight of 19,945 pounds, consisted of six longitudinal passes down the middle of the area, with each successive pass adjacent to the previous one. For this test, the tires on the truck were inflated to 60 psi, and the truck was operated at speeds of 25 to 35 mph. Also, sharp turns were made at the end of each pass. There was no damage to the surface in this test.

Next, the truck was loaded with a cargo of 20,000 pounds, and the tire pressure was increased to 70 psi. Six side-by-side, longitudinal passes at speeds of 30 to 40 mph caused no surface damage. Then, at speeds of 30 to 40 mph, the truck was driven in a serpentine pattern from Station 70+00 to Station 0+00 and return. In this test, there was no tire penetration in the compacted surface. The final test run, made between Stations 70+00 and 50+00, was a tight-turn serpentine pattern at speeds of 15 to 20 mph, with the reverse pass crossing the forward pass at right angles. Except for one soft spot, there was no surface penetration. At Station 60+00, the first pass caused a slight indentation; then, the second pass caused abrasion in the center of the crossing. The penetration was not sufficient to slow the truck, but was deep enough to destroy the surface.

## LC-47 Test

The day after the truck tests, the area was covered with 8 inches of new, fluffy snow and drift snow, which had to be removed before aircraft testing. The snow was graded into windrows with the snowplane and removed with the snowplow carrier. The surface was then treated with the pneumatic-tired roller.

On 3 February, an LC-47 aircraft weighing 25,000 pounds, with its main tires inflated to 60 psi, made a ski landing on the 0-70 test area. Touching down at Station 5+00, the aircraft rolled out at Station 50+00. The pilot raised the skis (Figure 16), made a full-circle turn on wheels, and taxied down the center of the runway to Station 3+00. Another full-circle turn was made at that station, and then the aircraft was taxied at full throttle up the center of the runway to Station 50+00, where it lifted off. The pilot circled and landed the plane on wheels at Station 10+00 and rolled out at Station 55+00. Following a full-circle turn at Station 58+50, the pilot taxied back to Station 1+00, where he turned around and made a second wheeled takeoff and landing. Two more wheeled takeoffs and landings were made, including one downwind. Following a serpentine taxi test in both directions, the pilot completed the tests with three more wheeled takeoffs and landings.

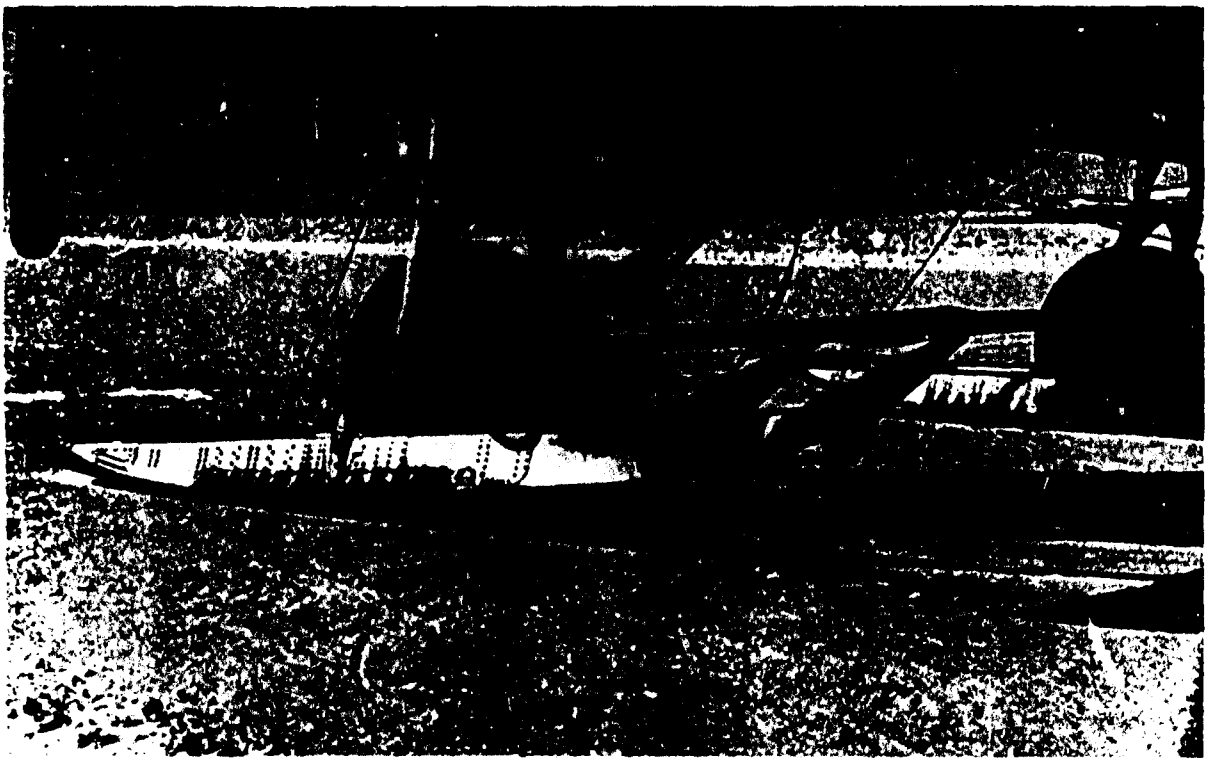


Figure 16. An LC-47 aircraft on wheels during taxi tests on 3 February 1964.

Through the traffic tests, the LC-47 rolled easily, and the pilot showed favorable reaction to the condition of the runway. Inspection of the runway following the tests disclosed several locations where the surface had been scuffed. In making a tight turn at Station 58+00, the outboard main wheel twice plowed 1 to 2 inches into the surface for distances of 3 to 4 feet. Examination of these areas, and several others along the wheel track between Stations 55+00 and 5+00, showed that the surface was breaking down in the top 2 to 4 inches where the Ramm hardness was 300 to 360R. Surface support appeared to be marginal where the hardness in the top 4 inches was 360 to 400R and good where it was 400 to 460R. All damage, except at a weak area near the center of the runway at Station 2+00, was at the surface. That is, there was ample strength in the compacted snow to support the aircraft on wheels.

The weak area at Station 2+00 was rutted up to 5 inches deep by the wheels of the LC-47 during a turn. The depth of the rut was not enough to place the weight of the aircraft on the skis, but it did cause some loss of control in the turn.

#### LC-130F Tests

Following the LC-47 tests, several inches of snow fell on the 0-70 runway, and some light drifting added to the accumulation. In anticipation of further aircraft tests, the new snow was compacted and leveled with the smooth drag.<sup>11</sup> The snow blower was used to clear some of the drift from the edges of the runway.

Late in the afternoon of 7 February 1964, an LC-130F weighing 100,000 pounds, with its main tires inflated to 80 psi, made a ski landing on the 0-70 test area. Touching down at about Station 5+00, the aircraft rolled out at Station 40+00. There, the pilot retracted the skis (Figure 17) and taxied on wheels in a serpentine pattern from Station 40+00 to Station 67+00, and back to Station 60+00. At that point, the skis were lowered and the plane departed.

While on skis, the plane crossed on the older 4-layer portion of the area; all of the wheeled taxiing test was on the newer 2-layer portion. Also, routine snow tests indicated that this portion, which had been processed under adverse conditions in late December, contained lens-shaped zones of weakness. These zones, or holidays, which were 8 to 10 inches below the surface and 2 to 4 inches thick, were attributed to incomplete processing of the DF-64 layer. The underlying layer of processed snow, which was processed in DF-63, was hard and strong.

Except for three wheel breakthroughs (Figure 18) which occurred between Stations 44+00 and 67+00, the aircraft wheels made little or no indentation on the compacted snow during the 3,400-foot taxi test. Even though the breakthroughs, consisting of 20- to 100-foot-long ruts, represented less than 3% of the total taxi run, they were sufficient to classify the test as a failure.



Figure 17. An LC-130F aircraft on wheels during taxi tests on 7 February 1964.

The areas around the failures were tested for hardness and shear to determine the minimum thickness and bearing capacity required in compacted snow to support the tandem main wheels on an LC-130F with its tires inflated to 80 psi. Analysis of the data indicated that the 8- to 10-inch-thick layer of processed snow over the holiday areas in the DF-64 layer failed where the average hardness of the snow was 460R or less. Where the average hardness in this snow ranged between 470R and 480R, support was marginal and where it averaged 490R or more, no failures occurred. Shear tests indicated that the average bearing capacity of this 8- to 10-inch layer of snow was 56 psi where its average hardness was 460R, 80 psi where its average hardness was 480R, and 89 psi where its average hardness was 490R. In contrast, at the time of the tests, the hardness in the underlying 18-inch-thick, year-old, DF-63 layer of compacted snow (Figure 11) ranged between 590R and 1900R, for an average of 1245R.

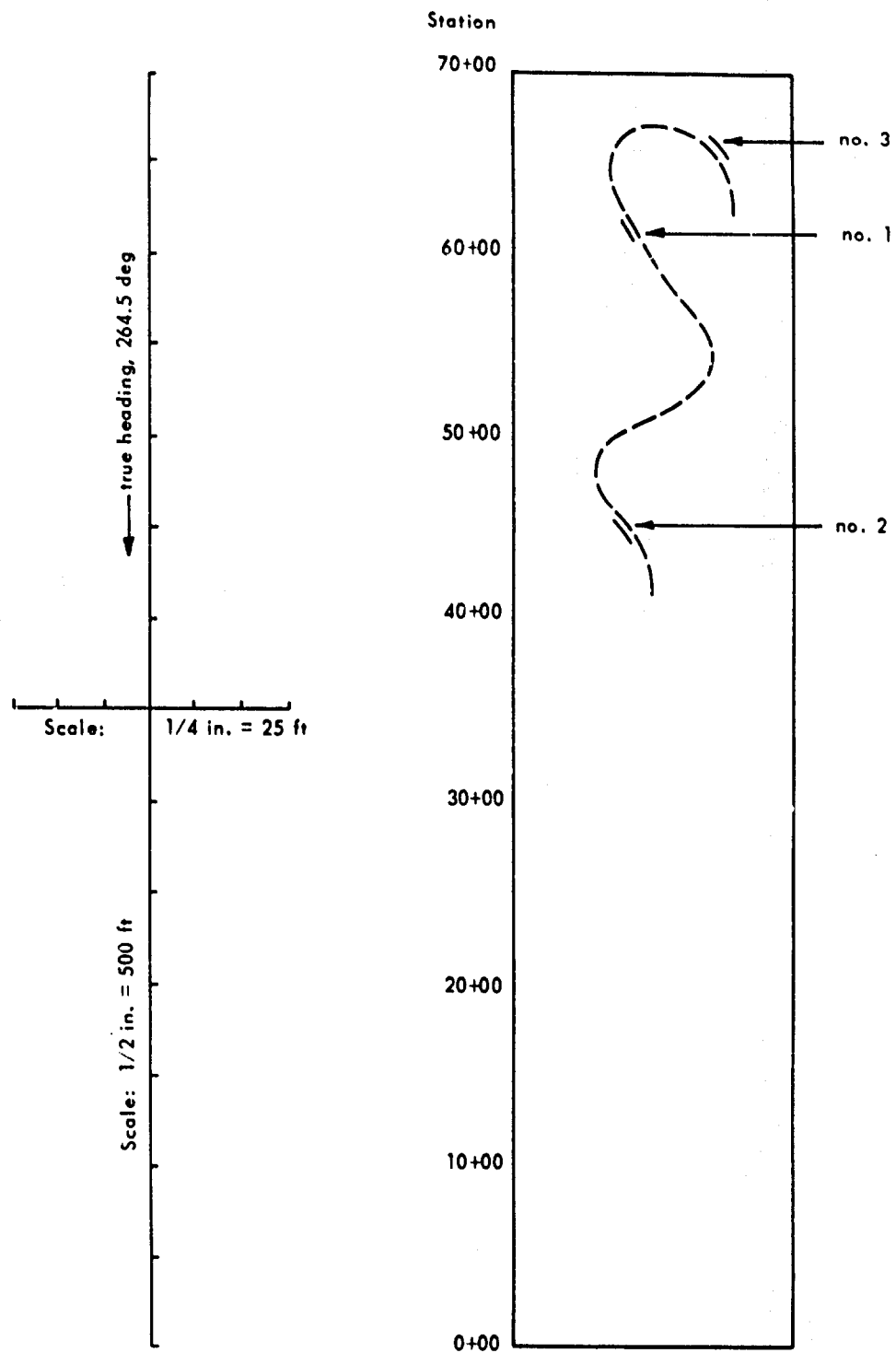


Figure 18. Location of wheel tracks and failure areas during LC-130F taxi tests on 7 February 1964.

## FINDINGS AND CONCLUSIONS

1. Suitable weather, adequate field supervision, trained personnel, and quality control were essential for successful snow compaction.
2. An 8- to 10-inch-thick layer of compacted snow, with an average hardness of 480R and a bearing capacity of 80 psi, would provide marginal support for the tandem main wheels of an LC-130F aircraft with its tires inflated to 80 psi.
3. With one-third fewer passes, the new Model 36/42 snow mixer would produce compacted snow with a density of  $0.60 \text{ gm/cm}^3$  compared with the  $0.53 \text{ gm/cm}^3$  snow produced with the older Model 42 mixer.
4. The Model 40 towed snowplow carrier was suitable both for rapid transport of fill snow when elevating a snow runway and for rapid removal of drift snow on a compacted-snow runway.

## PART V. SUMMARY

### FINDINGS

1. During the DF-61 - 64 trials, high-strength snow capable of supporting wheel loads up to 90 psi and gross loads up to 100,000 pounds was produced with the Navy cold-processing techniques; however, to produce uniformly stronger snow without processing misses with these techniques requires the following:
  - a. Modern, efficient snow-compaction equipment
  - b. Adequate supervision and trained operators
  - c. Quality control during processing
  - d. Good visibility and below-freezing temperatures during construction and age-hardening
2. Uniformity and strength of properly processed snow improves with time under favorable temperature conditions.
3. A 10-inch-thick layer of compacted snow with an average hardness of 480R, or a bearing capacity of 80 psi, will provide marginal support for aircraft grossing up to 100,000 pounds with their main tires inflated to 80 psi.
4. The surface of a compacted-snow runway must have a bearing capacity of 25 psi or more in the top 3 to 4 inches to support 90-psi tire loads without rutting.
5. The Model 36/42 snow mixer introduced late in the DF-64 trials shows considerable promise of producing denser, stronger compacted snow than the previous mixers used in these trials.
6. The Model 40, towed snowplow carrier introduced in the DF-64 trials appeared suitable for both elevating and clearing compacted-snow areas.
7. Elevated areas in fields of drifting snow accumulate little drift until the surrounding area reaches the same level.

## CONCLUSIONS AND RECOMMENDATIONS

1. The antarctic snow-compaction trials should be continued to fully explore the capabilities of the new processing and elevating equipment introduced in DF-64. The objective should be the production of an elevated, multilayered, compacted-snow runway of uniform strength capable of supporting aircraft of gross weights up to 155,000 pounds and with main tires inflated up to 135 psi.
2. A hard, tough wearing surface must be developed for compacted snow subjected to heavy wheel loads.
3. A compacted-snow area must be subjected to repetitive tests with aircraft throughout an antarctic summer season to determine its suitability under changing climatic conditions and to determine the degree and type of maintenance required for its continued use.

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## REFERENCES

1. Task Force 68, U. S. Lant Flt. Report of Operation Highjump, U. S. Navy Antarctic Development Project, Washington, D. C., June 1947.
2. U. S. Army, Snow, Ice, and Permafrost Research Establishment. Report No. 13: Snow Compaction, by A. Taylor. Wilmette, Ill., Jan 1953.
3. L. W. Gold. "The strength of snow in compression," Journal of Glaciology, vol. 2, no. 20, Oct 1956, pp. 719-725.
4. U. S. Naval Civil Engineering Laboratory. Technical Report R-298: Snow compaction in Antarctica — Roads on snow-covered sea ice, by E. H. Moser, Jr. Port Hueneme, Calif., Mar 1964.
5. ———. Technical Report R-114: Snow compaction: Techniques, by E. H. Moser, Jr. Port Hueneme, Calif., June 1962.
6. Task Force 43 U. S. Naval Support Force, Antarctica. Operation Plan No. 1-61 for Operation Deep Freeze 62. Washington, D. C., Aug 1961.
7. U. S. Naval Civil Engineering Laboratory. Technical Report R-106: Dual-rail snow tracks for the Caterpillar D-4 tractor, by A. L. Scott and D. Taylor. Port Hueneme, Calif., Oct 1960.
8. ———. Technical Note N-330: A dual-rail track system installed on Caterpillar D2 LGP snow tractors, by J. J. Doman, J. R. Dawes, and D. Taylor. Port Hueneme, Calif., Apr 1959.
9. ———. Technical Report R-108: Snow-compaction equipment: Snow mixers, by R. C. Coffin, Jr., and E. H. Moser, Jr. Port Hueneme, Calif., Jan 1961.
10. ———. Technical Report R-107: Snow-compaction equipment: Snow rollers, by J. B. Camm. Port Hueneme, Calif., Jan 1961.
11. ———. Technical Report R-109: Snow-compaction equipment: Snow drags, by J. B. Camm. Port Hueneme, Calif., Oct 1960.
12. ———. Technical Report R-110: Snow-compaction equipment: Snow planes, by E. H. Moser, Jr. Port Hueneme, Calif., Feb 1961.
13. ———. Technical Note N-610: Snow-transport equipment — Tractor-mounted snowplow tests, by R. W. Hansen. Port Hueneme, Calif., June 1964.
14. ———. Technical Report R-113: Snow compaction — Design criteria and test procedures, by E. H. Moser, Jr. Port Hueneme, Calif., Apr 1964.
15. ———. Technical Report R-007: Experimental Arctic operation HARD TOP II, 1954, by W. R. Reese. Port Hueneme, Calif., Dec 1955.
16. ———. Technical Report R-417: Snow-transport equipment — Model 40 towed-type snowplow carrier, by R. W. Hansen. Port Hueneme, Calif., Dec 1965.

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